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PART I

A SURVEY OF COAL PREPARATION PRACTICE IN THE COAL MINING INDUSTRY OF ALBERTA.

PART II

STUDIES IN FUNDAMENTALS RELATING TO THE CLEANING OF FINE COAL.

BY

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A Thesis

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Part I. A SURVEY OF COAL PREPARATION PRACTICE IN THE COAL MINING INDUSTRY OF ALBERTA.

General Introduction

This research originated in a survey of the methods employed in the mines of Alberta to prepare coal for the market. For whatever fuel purpose coal is used, almost invariably the associated mineral matter may be considered to be disadvantageous. A possible exception is when coal is burned in chain grate boilers with air preheated to a fairly high degree, under which conditions, fusion of the ash may materially reduce the life of the grate and give rise to considerable working difficulties. In such a case it is better to use a coal containing an appreciable quantity of mineral matter provided, of course, that the softening temperature of the ash is not too low.(1)

Broadly speaking, in Alberta, two kinds of coal are distinguished for marketing purposes, namely, sub-bituminous and bituminous coals. The sub-bituminous coals which are mined in the plains areas are of low grade relative to the coals of the bituminous type. The moisture and oxygen contents are high and accordingly the calorific values are low. Although this type of coal on mining is fairly hard and blocky, on storage it dries out and as a result, the pieces disintegrate and considerable quantities of fine material are produced.

The sub-bituminous coals of Alberta, however, are relatively clean, generally speaking, containing quantities of ash of the order of 6 - 10 per cent.

On the other hand, the bituminous coals occurring principally in the foothills and mountain regions, apart from a high content of mineral matter, are of high grade, that is to say, generally speaking, they are of a bituminous nature and in some restricted localities, even approach semi-anthracite. The calorific values of the mineral-matter-free coal are high and of course the coals contain relatively small quantities of water (below about 2 - 4 per cent. on mineral-matter-free coal).

Certain of these coals coke to a variable degree. They store well without the production of large quantities of fine material. Unfortunately, however, in many instances, owing to excessive faulting and folding of the seams, the coals as mined are very friable, so that a relatively large proportion of the output of a mine may be of small size.

The Importance of Fine Coal

It will thus be seen that, both in the bituminous and sub-bituminous fields, the production of fine coal presents problems. As will be shown in more detail later, the practice in the sub-bituminous field appears to be to sell as much fine coal as possible and to discard the remainder. Various proposals have been made for the economic utilization of this material. Based on a considerable

amount of scientific investigation, it has been proposed that the material should be carbonized and the resulting char briquetted with a suitable binder. On carbonization at about 600°C. the yield of char is only about 50 per cent., so that if the original slack coal contains 10 per cent. of ash, the char will, of course, contain 20 per cent. of ash.

Carbonization in this way removes the water as well as a large proportion of the oxygen, and the calorific value is increased proportionately. An alternative proposal has been that the material should be dried, briquetted with a binder and then carbonized. In this way a solid, blocky, smokeless fuel may be produced. This procedure may, of course, include the addition of suitable proportions of a coking coal prior to briquetting.

Whatever the procedure adopted, it will be obvious that the lower the mineral matter content of the original coal, the better will be the carbonized product.

The cleaning of finely-divided bituminous coal has always presented a problem in coal preparation and considerable attention has been devoted to it. The practice in the past has varied considerably, dependent, of course, on the economics of new processes relative to the conditions peculiar to a particular mine. At one time it was not uncommon to screen out the finest coal before wet washing the remainder, and then to return and mix this fine material with the finest washed product.

One advantage in this procedure was that dedusting the coal before washing minimized the difficulties inherent in conventional

wet-washing plants due to contamination of the washery water with finely-divided suspended matter. In some instances, an outlet was found for the fine coal for steam-raising purposes at the mine itself.

When the froth flotation process was developed, the finest coal could be cleaned by this means. In this case, the clean coal-froth might be dewatered to some degree by mixing it with the smallest size coal washed in the conventional manner and allowing the material to drain. Rotary filters have now come into use for dewatering the coal froth. The difficulties of handling and dewatering a frothed product have favoured the fairly rapid development of air cleaning tables and at the present time these are finding fairly wide application.

If one compares the froth flotation process and the air cleaning table, it will be clear that the latter has certain obvious advantages. For example, it is somewhat costly to dewater a froth floated product. In Alberta, because of climatic conditions, wet coal, even of larger size may give rise to considerable difficulties in handling and transport during the winter months. The air table also surmounts substantially the problems in connection with the handling and utilisation of the coal slurries which are produced in ordinary wet washing plants.

Air cleaning, on the other hand, is not too satisfactory with the very finest coal, certainly not with coal less than 1/16 in., nor of course can one hope to obtain a product by this means as low in mineral matter as from a froth flotation plant. Also air cleaning tables are invariably dusty in operation so that auxiliary plant has

to be provided to cope with this nuisance. Unless the tables are maintained in an efficient condition, the nuisance from this source can be very real. One instance of this has actually been observed during the course of a visit to one of the bituminous mines in Alberta.

Finally, cleaning by means of air tables is, on the whole, cheaper than cleaning either by wet washing or froth flotation.

Dense Medium Washers

Special mention must be made of dense medium washers which probably represent the latest development in coal cleaning processes. Some indication of the reasons for this development is given in a paper published by A. Grounds and W. Reed entitled "Progress in Coal Preparation Practice"(2). This paper discusses the survey of coal cleaning methods in use in British coal-fields which the newly formed British National Coal Board is at present conducting. The ultimate purpose of the survey is to increase the overall efficiency of coal cleaning. With the poorer quality of the coal seams mined in Britain and with an increasing degree of mechanization, the proportion of dirt and fine material in the run-of-mine coal has increased, whilst the average overall size of the material has decreased. The older coal cleaning plants are incapable of obtaining the rated output with this larger proportion of dirt so that the output has fallen considerably. Also it is becoming more common to crush and recycle the "middlings".

The changing character of the run-of-mine coal has made more popular wet cleaning on the dense-medium principle and also an increasing amount of dry cleaning for treatment of fine coal. As much as 15 per cent. of all coal which is cleaned is treated in dense medium plants and this proportion is likely to increase in the future.

As far as is known, dense media washing in units of large throughput has not developed to anything like the same extent on this continent as it has in Europe.

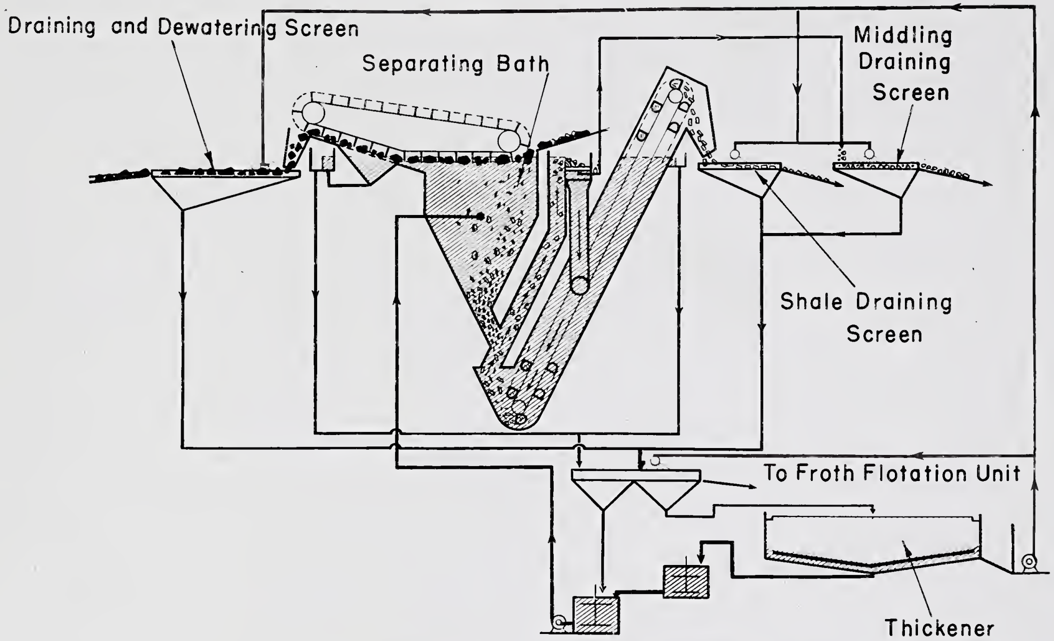
In Alberta, as far as is known, only one dense medium plant is in operation, although it is understood that the installation of a second is under consideration. In order that the development and design of the dense medium washer may be understood better, it is thought appropriate here to include a brief description of one of the most recently developed plants, namely the Barvoys Dense Medium washer, an installation of which was visited in Britain.

The Barvoys Dense Medium Plant

The plant, shown diagrammatically in Figure 1, consists essentially of a conical-shaped separating bath containing the separation medium, and in which the separation of clean coal from shale takes place. The medium employed consists of a suspension of a mixture of shale, generally available from mining operations, and barytes, ground to pass a 200 mesh sieve. The shale has a density of about 2.4 and the barytes a density of 4.2. The suspension employed usually has a volume ratio of shale to barytes of 2:1.

Figure 1.

THE BARVOYS DENSE MEDIUM PLANT.



THE BARVOYS DENSE MEDIUM PLANT

The specific gravity used in cleaning generally falls within the range of 1.15 to 1.9.

Separation in the washer takes place in two stages. In the first stage, the coal is floated off from the remainder of the raw feed, which is then separated in the second stage into a middlings product and shale. The raw coal is fed to the top of the separating bath which contains the medium, the specific gravity of which is adjusted to suit the type of coal being washed. That portion of the raw feed which has a specific gravity less than that of the medium floats in the suspension and is gently scraped from the surface of the medium and passed over a draining screen, falling through onto a dewatering screen where it is sprayed with water to free it from any adhering medium. It is then allowed to dry naturally.

Material sinking to the bottom of the cone passes from there into a separate section of the bath in which a vertical current of medium is maintained. This vertical current effects a separation of the shale from the middlings, which are carried upwards to a separate discharge and passed to a vibrating screen on which it is first sprayed free of medium and then drained.

Recovered middlings are usually crushed to free the intergrown coal and then returned to the bath for further treatment. The shale which falls against the upward current passes into a bucket elevator which lifts it out of the bath and in turn delivers it to a spraying and dewatering screen.

The dilute medium coming from the three washing screens passes

through a 1/3 inch screen in order to remove the larger material which can be sent to a froth flotation unit, and the dilute medium passing through the screen goes to a thickener.

The overflow from the thickener is used in the sprays, and the thickened medium is brought to the correct specific gravity and returned to the bath.

An important feature of the process is the use of both upward and downward currents of medium in the bath, to accelerate and improve the primary separation of clean coal from the raw feed. This condition is produced by introducing the feed of circulating medium at a point midway between the top and bottom of the bath and controlling the amount of the medium flowing upwards and downwards by means of two adjustable weirs. The velocity of flow in each direction is maintained at about 12 feet per hour.

With some of the coals being produced in Britain, where shale and coal can be sharply separated, the Barvoys dense medium washer under good operating conditions will give a shale containing no detectable amount of coal and a clean coal product which will not have an ash content differing by more than 0.06 per cent. from that theoretically possible.

Relative to the treatment which coal undergoes in other types of plants, in this plant the coal receives gentle handling and the breakage is minimized. The Barvoys dense medium washer has been selected for the treatment of coals which are particularly soft and friable.

Coal Survey in Alberta.

Considering the above account of some of the important factors in coal cleaning, it will be recognized that before any specific problem could be selected as most suitable for investigation on a laboratory scale, a survey was necessary of the actual position with regard to the preparation of coal for the market in the Province of Alberta. Accordingly, with the co-operation of the Domestic and Bituminous Coal Operators organizations, a questionnaire was compiled and circulated for completion and return. The questions asked in the questionnaire were so designed as to give information on the salient features of the methods of coal preparation used in the mines individually.

The form of the questionnaire is set out on the next page.

QUESTIONNAIRE ON PREPARATION OF COAL FOR THE MARKET

1. Name of company ....

2. Name of mine or mines ....

3. Location of mines or mines ....

4. Number or names of seams worked ....

5. Average daily output of coal obtained from each individual seam (long tons).

6. Please state if coals from different seams are prepared separately for the market or the whole output combined for treatment .....

7. Please state details of screening plant used, for example, the kinds of screens employed, whether gravity bar, shaker, trommel, vibrating, etc. and describe their arrangement ....

8. Please state size and shape of apertures in screens ....

9. Please state if dust-proofing of coals is practised. If so, please give details of methods employed and nature and quantities of dust-proofing agents employed ....

10. Please state nature of any further treatment given to separate screened products ....

11. Please state if a coal breaker is used and if so the nature of it, e.g. whether a jigging type pick breaker, horizontal type pick breaker, jaw crusher, swing hammer mill, roll crusher, etc.

12. If breaking employed, please state maximum size of product ....

13. If coal cleaning is practised, please describe the sequence of coal cleaning operations, providing, if possible, a flow sheet of the material during treatment, a description of the kind of plant used and a statement of the sizes of the products ......

14. If drying of coal is practised, please describe the plant used for the purpose ....

15. If any particular treatment is given with respect to coal slurries or washery water, please describe the nature of it. For example a statement might be given that froth flotation is used as supplementary to normal wet washing or special methods employed for settlement with or without the use of flocculating agents ....

16. Please give the market names used to describe the various products. If details can be given of the degree of cleaning normally achieved in terms of ash contents of raw coal, clean coal and rejected material and yields of the products per ton of coal treated, these would be appreciated. Some indication of the nature of the markets served by the separate products would also be of value.

17. Please state the nature of the problems you encounter in your processes for preparing coal for the market.

Name .... Address ....

Date ....

Observations on Questionnaire

The following observations may serve to explain the reasons for some of the information sought in the above questionnaire:

(1) Items 4 and 6

The coal from different seams may show different washing characteristics. Whilst it was recognized that it was unlikely in any case that individual seams would be treated separately, confirmation was required on this point.

(2) Item 5

It was thought that a return of data on the average daily output of coal from individual seams would serve, not only as a measure of the size of the industrial undertaking, but when considered in conjunction with the other information, would probably indicate whether the installation of a coal cleaning plant might reasonably be considered in any particular case.

(3) Items 7 and 8

Screening practice elsewhere has not followed a uniform course, so that size and nomenclature show fairly wide variations. It is known that one purpose of the survey in Britain is to achieve uniformity in nomenclature and ultimately in the sizing of coal.

(4) Items 9 and 10

The dust-proofing of coal in Alberta appears to be of importance principally from the point of view of dust control. Where coal is used for industrial purposes, in the manufacture of, for example, paper, textiles or food, the product may be damaged if

the atmosphere is dusty. In the home, dust is a nuisance in stoker fuel and increases the cost of maintenance of the plant and of keeping the home in a clean condition.

It is not possible here to include any description of the processes employed, except briefly to say that calcium chloride, oil or other petroleum products are usually used for this purpose. For an account, reference may be made to the literature on the preparation of coal for the market.

This item was included in the questionnaire in order to make the questionnaire more inclusive. The same remark applies to Item 10 except, of course, unless screening preceded washing.

(5) Items 11 and 12

The demand for coals of different size may vary from time to time so that commonly, large-sized coal may be crushed to produce more suitable sizes as dictated by market requirements. Also, speaking generally, coal cleaning processes have an upper size limit. If any coal above this size limit is to be washed, the material must, of course, be passed through a suitable coal breaker.

Breakers vary in efficiency and the questionnaire included a request for information on the type of breaker employed.

(6) Item 13

This item is one of the most pertinent in the questionnaire, since full returns under this item would make possible a complete and detailed analysis of coal cleaning methods in the province.

(7) Item 14

Some explanation has already been given of the importance of coal drying in Alberta.

(8) Item 15

This item was included to supplement information particularly on wet washing.

(9) Item 16

This item was included to obtain, if possible, some ideas of the efficiency of operation of existing plants.

(10) Item 17

This item was included with a view to elucidating other lines of investigation for study later.

Analysis of Returns from Questionnaire

Questionnaires were circulated to all the mines in both the sub-bituminous and bituminous coal-fields of Alberta. The number of completed questionnaires returned was not very satisfactory. In all, 30 completed returns were received, 16 from the sub-bituminous and 14 from the bituminous mines. The information in the returns has been summarized in the following tables.

TABLES I - VI

INFORMATION FROM QUESTIONNAIRES

TABLE I

BASIC DATA FOR SUB-BITUMINOUS MINES

Name of Company		Seams Worked * Strip	Daily Output (Long tons)	Combined or Separate Treatment	Types of Screens	Screen Sizes	Dustproofing	Treatment of Screened Products	Coal Breaking	Flow of Products	Drying	Marketed Products	Treatment of Coal Slurries	Problems Stated
Century Coals Limited	Atlas Mine	One	700	-	Shaker	4",2",1¼",¾" all round holes	None	None	None	Main flow of coal is handpicked	None	Egg 4" - 2" Nut 2"-1¼" Stoker 1¼"-3/4" Slack 3/4"-0"	-	Coal Breaking
	Commander Mine	Lower Seam	700	-	Bar, shaker Vibrating	4",2",1" round 5/8" square	None	None	None	Handpicking practised	None	Lump +4" Egg 4" - 2" Nut 2" - 1" Stoker 1" -5/8" Slack 5/8" -0"	-	-
Western Gem & Jewel Collieries Ltd.		Drumheller Lower Seam	450	-	Shaker Rotary	4" round 2" round 1" square 5/8" square	None	None	None	Handpicking	None	Lump +4" Egg 4" - 2" Nut 2" - 1" Stoker 1" - 5/8" - 5/8"	-	-
Rosedale Collieries	Rosedale Mine	No. 1 No. 5	530	Combined	Shaker Rotary	4" round 2" round 1¼" square 3/4" square	None	Lump, Egg and Nut sizes handpicked	Roll Crusher being installed	-	None	Lump +4" Egg 4" - 2" Nut 2" - 1¼" Stoker 1¼"- 3/4" Slack - 3/4"	-	Cleaning
	Star Mine	Drumheller Lower Seam	400	-	Shaker	4" and 2"	None	None	None	-	None	Lump +4" Egg 4" - 2" Nut Slack - 2"	-	None
Midland Coal Co. Ltd.		No. 1	800 - 1000	-	Shaker (Marcus) Rotary	4" round 2" square 1¼" square 5/8" square	None	Breakage removed over bar screens prior to loading Lump and Egg handpicked	Roll Crusher used previously	-	None	Lump +4" Egg 4" - 2" Nut 2" - 1¼" Stoker 1¼"- 5/8" Slack - 5/8"	-	Cleaning
Monarch Coal Co. Ltd.		Lower Seam	400	-	Shaker	4",2",1" round and ½" square	None	None	None	-	None	Lump +4" Egg 4" - 2" Nut 2" - 1" Stoker 1" - ½" Slack -½" & -1"	-	None

(Table I continued)

Name of Company	Seams Worked * Strip	Daily Output (Long tons)	Combined or Separate Treatment	Types of Screens	Screen Sizes	Dustproofing	Treatment of Screened Products	Coal Breaking	Flow of Products	Drying	Marketed Products	Treatment of Coal Slurries	Problems Stated
Great West Coal Co. Ltd.	Clover Bar Seam	500	-	Perforated-Plate. Shaker Rotary	4" 2" round 1 1/8" round ½" round	None	Breakage removed prior to loading by screening.	None	-	None	Lump +4" Screened Mine Run +2" Egg 4" - 2" Nut 2"- 11/8" Stoker 11/8"-½" Slack -½"	-	None
Inland Coal Co. Ltd.	Carbon Seam	175	-	Bar Screen Rotary	None given	None	None	None	-	None	No information	-	None
Maple Leaf Coal Co. Ltd.	East Coulee Seam	250	-	Vibrating	None given	None	None	None	-	None	No information	-	None
Newcastle Collieries Ltd.	No. 1 Drumheller	400	-	Shaker Rotary	4" and 2" 1" and ½"	None	Handpicking	None	-	None	No information	-	None
Arcadia Coal Mines Ltd.	No. 1 Drumheller Lower Seam	135	-	Shaker Rotary	4",2",and 1½" 5/8"	None	None	None	-	None	No information	-	None
Lakeside Coals Ltd. Robb Mine	Val d'Or	500	-	Vibrating	4" square 2" square 1" square 3/8" square	None		Pick Breaker reduces to 12" size	-	None	Lump +4" Egg 4" - 2" Nut 2" - 1" Stoker 1"- 3/8"	-	None
Wabamun Mine	Pembina	300	-	Shaker Rotary	4" round 2" round 1" round 7/16" round	None	Calcium Chloride treatment	Jaw Crusher	-	None	Lump +4" Egg 4" - 2" Nut 2" - 1" Stoker 1"- 7/16"	-	None
Minute Coal Co.	top seam	91	-	Shaker	4" round 2" round 1" round 3/4" round	None	None	None	-	None	No information	-	Cleaning
Kleenbirn Collieries Ltd.	Two	900 - 1000	-	Shaker Vibrating (Ty-Rock)	4" round 2" round 1¼" x 1" 3/8" square	None	None	None	-	None	Lump +4" Egg 4" - 2" - 2" - 1" - 1"- 3/8"	-	-

TABLE II

BASIC DATA FOR BITUMINOUS MINES

Name of Company	Seams Worked * Strip	Daily Output (Long tons)	Combined or Separate Treatment	Types of Screens	Screen Sizes	Dustproofing	Treatment of Screened Products	Coal Breaking	Flow of Products	Drying	Marketed Products	Treatment of Coal Slurries	Problems Stated
Bighorn and Saunders Creek Coal Co.	One Seam	150	-	Shaker	From 12" x 8" oval to 3/4" round	None	None	None	-	None	Lump, Egg, Stove Nut, Slack	-	None
Alexo Coal Co.Ltd.	Saunders	120	-	Bar Shaker Rotary	1 5/8" 6"x 18" oval $2\frac{1}{2}$"x 12" oval 5/8" square 1 5/8" square	None	None	None	-	-	Lump, Egg, Nut Slack	-	None
Brazeau Collieries Ltd.	No. 2 Seam NO. 3 Seam No. 3 Seam*	376 735 700	Combined	Shaker (Marcus)	6" grid $\frac{3}{4}$" round $1\frac{1}{2}$" x $\frac{1}{4}$"	None	6"-3/4" Wetwashed 3/4"-$\frac{1}{4}$" Drycleaned 0 - $\frac{1}{4}$"Briquetted	None	-$\frac{1}{4}$" removed first.Remainder split to 6"-3/4" for wetwashing. 3/4"-$\frac{1}{4}$" for drycleaning. Cleaned products combined	Vissac Thermal Dryer	6"-$\frac{1}{4}$" plus briquettes	-	None
Hillcrest Mohawk Collieries Ltd.	No. 1 Seam No. 3 Seam	1350 200	Combined	Gravity Bar Vibrating	3" $1\frac{1}{4}$" 3/4" 7/16"	3% - 6% Calcium Chloride solution used	5"- $1\frac{1}{4}$" & 2"-$\frac{1}{4}$" washed in Vissac Jig $1\frac{1}{4}$"-3/4",3/4"-$\frac{1}{4}$" and $\frac{1}{4}$"- 0 cleaned on Air tables	Two roll crushers giving 5" & 3" products	Coal broken &+$1\frac{1}{4}$" sent to Jig washer. - $1\frac{1}{4}$"drycleaned. Wet coal dried by hot air.	Hot Air dryer	Ash content is reduced in cleaning from 14 - 19% in raw coal to 12-15% in clean coal. Markets are Railroad 85% Industrial 10% Domestic 5%		Separation medium said to be 1.52 Sp.Gr. The seams contain bone with an ash content of 20-30% floating at a Sp.Gr. of 1.52. Problems are separation problems

(2. Table II continued)

Name of Company	Seams Worked * Strip	Daily Output (Long tons)	Combined or Separate Treatment	Types of Screens	Screen Sizes	Dustproofing	Treatment of Screened Products	Coal Breaking	Flow of Products	Drying	Marketed Products	Treatment of Coal Slurries	Problems Stated
Canmore Mines Ltd.	Stewart Seam No. 4 Seam	300 900	Combined	Shaker (Marcus) Vibrating (Gyrex) Hummer	1½" round 2 5/8" round 7/8" square ¼" square	Viking Oil Process. 1 gal oil per ton of coal	Coal from ¼" upwards is handpicked. - ¼"- 0 coal is briquetted	None	-7/8" from Gyrex screen is rescreened over two Hummers; -¼"goes to briquetting plant; ¼"-7/8" goes to Marcus screen and is remixed with -1½".	None	+2 5/8" 2 5/8" - 1½" 1½" - ¼" Stoker -¼"in briquettes	-	None
West Canadian Collieries Ltd.	No. 1 Seam No. 2 Seam NO. 4 Seam	4000	Combined	Shaker Vibrating	4" 2" ½" ¼"	Solid Calcium Chloride 5 lbs/ton Spray oil 2½ gal/ton	0 -3/16" dried by heat drier. 3/16"-½" not commented on. ½"-6"dedusted with water on screens. +½"in dense medium washer 0 -3/16" in Brusset Jigs 3/16-½" Air tables	Roll crusher giving 6" product	0-3/16"cleaned in Brusset vacuum jigs. 3/16-½"cleaned on Air tables Over ½"cleaned in dense medium washer.	0-3/16" dried on shaker screens by upward hot gases. Over ½" dried on vibrating screens by downward hot air.	Mine run 0-6" Furnace 1½"-6" Steam 0-1½" Nut pea ¼-1½" Slack 0 -¼" Sea coal (dust) Briquettes	Coal slurries recovered by flotation Bird centrifuge used. Settling tank & drainage pools employed	None
Luscar Coals Ltd.	No. 2 Seam No. 3. Seam No. 4 Seam No. 5 Seam * Strip	150 450 150 nil 1000	Combined	Shaker (Marcus)	2½" round	None	+2½"' handpicked -2½" air cleaned	None	Two air cleaning tables employed for coal below 2½" (55 tons per hr. each) This coal is then remixed with the 2½"for sale as run-of-mine.	None	Run of Mine		Freezing of fine coal

Name of Company	Seams Worked * Strip	Daily Output (Long tons)	Combined or Separate Treatment	Types of Screens	Screen Sizes	Dustproofing	Treatment of Screened Products	Coal Breaking	Flow of Products	Drying	Marketed Products	Treatment of Coal Slurries	Problems Stated
Cadomin Coal Co. Ltd.	No. 1 Seam	1600	Combined	Vibrating Hummer	1 5/8" 3/8"	Viking oil process	6"-1 5/8" to be washed in Vissac Jig when completed.	30" x 48" Roll crusher used to break down to 6"	Run of mine separated into 6"-1 5/8" for wet washing & below 1 5/8" for dry cleaning. Various size ranges are produced according to requirements	McNally-Vissac Dryer hot air blasts forced through bed in pulsations	Run of Mine 6" - 0" Lump 6"-1 5/8" Stoker 1 5/8"-¼" Slack 1 5/8"-0"	-	None
Lethbridge Collieries Ltd. Galt Mine	Lethbridge Seam	900	-	Stationary bar Shaker Vibrator Hummer	3/4" 4" 1 1/8" 5/8" 1 1/8" 5/8" ¼"	None	Picking tables for over 4" and 4"-1 1/8" Spirals used on 4" - 1 1/8" Air tables for 1 1/8"-5/8" and 1 1/8"-¼" and 1 1/8"- 0.	Double roll crusher	Run of mine passed over 3/4" screen +3/4" screened on 4" screen. +4" is handpicked -4" screened over 1 1/8" screen 4"-1 1/8" cleaned over spirals 1 1/8"-3/4" remixed with - 3/4" and separated into 1 1/8"-5/8" & 5/8"-¼" for air cleaning.	None	Lump +4" Egg 4"- 1 1/8" Stoker 1 1/8"-5/8" Stoker 1 1/8"-¼" Pea Slack 1 1/8"-0" Slack 5/8"-0" Fine Slack ¼" - 0"	-	Separation of bone coal (ash content 16-20%) from clean coal (ash content 9-10%)
Standard Mine	Lethbridge Seam	900	-	Bar Shaker Rotary	1¼" 4" round 1 3/4" 3/4" round 3/4" round 3/8" round	None	1 3/4" - 3/4" on spiral separators 1 3/4"-4" and over 4" is handpicked	None	Run of mine passed over 1¼" bar screen +1¼" screened on 4" screen and +4" handpicked. The -4" is screened over 1 3/4" screen the 4"-1 3/4" being handpicked and the -1 3/4" being mixed with the - 1¼" From this the 1 3/4"-3/4" is cleaned on Spirals, remainder being slack	None	Lump +4" Egg 4"-1 3/4" Pea 1 3/4"-3/4" Stoker 3/4"-3/8" Slack 3/4"-0 Fine Slack 3/8" - 0	-	Separation of bone coal (ash content 16-20%) from clean coal (ash content 9-10%)

(4. Table II continued)

Name of Company	Seams Worked * Strip	Daily Output (Long tons)	Combined or Separate Treatment	Types of Screens	Screen Sizes	Dustproofing	Treatment of Screened Products	Coal Breaking	Flow of Products	Drying	Marketed Products	Treatmnt of Coal Slurries	Problems Stated
Foothills Collieries Ltd.	Val d'Or	500	-	Shaker Rotary	4" 2" 1" $\frac{1}{2}$"	None	None	Contemplated	+4" removed first in shaker Remainder picked & separated into 4"- 2", 2"- 1", 1"- $\frac{1}{2}$" and $\frac{1}{2}$"- 0 on rotary screen	None	Lump, Egg, Nut Stoker, Slack	-	None
McLeod River Hard Coal Co. McLeod River Mine	Val d'Or	1000	-	Shaker (Marcus) Rotary	5" round $2\frac{1}{2}$"round 1 5/8" square 3/8" square	None	None	None	+5" removed first, then 5" - $2\frac{1}{4}$", on shaker followed $2\frac{1}{4}$"- 1 5/8", 1 5/8"- 3/8", and 3/8"- 0" on rotary.	None	Lump, Egg, Nut Stoker, Fines.	-	Poor sizing in winter due to freezing of fine rotary screens
Mercoal Mine	Val d'Or	1000	-	Shaker Rotary	$2\frac{1}{2}$" round $1\frac{1}{4}$" 7/16"	None	None	None	Coal goes first to shaker Undersize from this is conveyed to rotary screen	None	-	-	None
McGillivray Creek Coal & Coke Co. Ltd.	No. 2 No. 4	605 270	Combined	Shaker Vibrating (Hummer)	4" round None given	None	+4" handpicked +1" wet washed	None	Coal goes first to shaker Undersize to vibrator screen Oversize from this screen goes to Baum Jig	Yes -3/8" size	Mine Run, Lump Stoker, Slack (2 sizes)	Slurries are first settled & then dewatered on screens	Drying of fine coal Dust collection & disposal screening

TABLE III

Screening Equipment - Sub-bituminous Mines

Name of Company		Type of Screens				
		Picking Belt	Shaker	Rotary	Bar	Vibration
Century Coals Ltd.	Atlas Mine	Yes	All sizes			
	Commander Mine	Yes	Yes		Yes	Yes
Western Gem & Jewel Co.		Yes	For Large Sizes	For Nut and Stoker		
Rosedale Collieries	Rosedale Mine	Yes	For Large Sizes	For Nut and Stoker		
	Star Mine		Yes			
Midland Coal Co.		Yes	For Large Sizes (Marcus)	For Egg, Nut and Stoker		
Monarch Coal Co.			All sizes			
Great West Coal Co.			Above 2" size	For Nut and Stoker		
Inland Coal Co.				Yes	Yes	
Maple Leaf Coal Co.						Yes
Newcastle Collieries Ltd.		Yes	Lump and Egg	For sizes smaller than 2"		
Arcadia Coal Mines			Lump, Egg and Nut	Stoker and Slack		
Lakeside Coals Ltd.	Robb Mine					Yes
	Wabamun Mine		Yes	Sizes smaller than 2"		
Minute Coal Co.			Yes			
Kleenbirn Collieries Ltd.			Yes			Ty-rock

TABLE IV

Screening Equipment - Bituminous Mine

Name of Company		Types of Screens				
		Picking Belt	Shaker	Rotary	Bar	Vibrating
Bighorn and Saunders Creek Collieries Ltd.		-	All sizes	-	-	-
Alexo Coal Co. Ltd.		-	Yes	Nut & Slack	Yes	-
Brazeau Collieries Ltd.		-	Marcus	-	-	-
Hillcrest Mohawk Collieries Ltd.		-	-	-	Yes	Yes
The Canmore Mines Ltd.		-	Marcus	-	-	Gyrex and Hummer
West Canadian Collieries Ltd.		-	Yes	-	-	Yes
Luscar Coals Ltd.		Yes	Marcus	-	-	-
Cadomin Coal Co. Ltd.		Yes	-	-	Yes	Niagara; Hummer and Ty-Rock
Lethbridge Collieries Ltd.	Galt Mine	Yes	Yes	-	Yes	Ty-Rock & Hummer
	Standard Mine	Yes	Yes	Yes	Yes	-
The Foothills Collieries Ltd.		Yes	Yes	Yes	-	Yes
McLeod River Hard Coal Co.	McLeod River Mine	Yes	Marcus Lump & Egg	Nut & Stoker	-	-
	Mercoal Mine	-	Yes	For small coal	-	-
McGillivray Creek Coal & Coke Co.		Yes	Yes	-	-	Yes

TABLE V

Coal Sizes - Sub-bituminous Mines

Name of Company		Daily Output	Lump	Egg	Nut	Stoker	Slack
Century Coals Ltd.	Atlas Mine	700	4"○	2"○	1 1/4"○	3/4"○	0"
	Commander Mine	700	4"○	2"○	1" □	5/8"□	0"
Western Gem & Jewel Co.		450	4"○	2"○	1" □	5/8"□	0"
Rosedale Collieries	Rosedale Mine	600	4"○	2"○	1 1/4"□	3/4"□	0"
	Star Mine	400	4"	2"	-	-	
Midland Coal Co.		900	4"○	2"□	1 1/4"□	5/8"□	0"
Monarch Coal Co.		400	4"○	2"○	1"○	1/2"□	0"
Great West Coal Co.		500	4"○	2"○	1 1/8"○	1/2"○	0"
Inland Coal Co.		175	□	□	□	□	
Maple Leaf Coal Co.		250	No Information Given				
Newcastle Collieries Ltd.		400	4"	2"	1"	1/2"	0"
Arcadia Coal Mines		135	4"	2"	1 1/2"	5/8"	0"
Lakeside Coals Ltd.	Robb Mine	500	4"□	2"□	1"□	3/8"□	0"
	Wabamun Mine	300	4"○	2"○	1"○	7/16"○	0"
Minute Coal Co.		91	4"○	2"○	1"○	3/4"○	0"
Kleenbirn Collieries Ltd.		1000	4"○	2"○	1"□	3/8"□	0"

○ Indicates round screen holes

□ Indicates square screen holes

TABLE VI

Coal Sizes - Bituminous Mines

Name of Company		Daily Output	Lump	Egg	Nut	Stoker	Slack
Bighorn and Saunders Creek Collieries Ltd.		-	← Oval holes from 12" x 8" to 1/4" →				
Alexo Coal Co. Ltd.		120	4"	1 5/8" □	(nut)	5/8" □	0"
Brazeau Collieries Ltd.		1811	6" ←	(locomotive)	→	1/4" (briquettes)	0"
Hillcrest Mohawk Collieries Ltd.		1550	5"	2"	1 1/4" 3/4"	7/16"	0"
The Canmore Mines Ltd.		1200		2 5/8" ○	1 1/2" ○	1/4"	0"
West Canadian Collieries Ltd.		4000	6" ○ ←	(Furnace) →	1 1/2" □ (nut pea)	1/4" □	0"
Luscar Coals Ltd.		1750	← Run - of - Mine →				
Cadomin Coal Co. Ltd.		1600	6" Bar		1 5/8"	1/4"	1 5/8" - 0"
Lethbridge Collieries Ltd.	Galt Mine	900	4" ○	1 1/8" ○ ←	(stoker) →	5/8" 1 /4"	1 1/8" - 0" 5/8" -0" 1/4" - 0"
	Standard Mine	900	4" ○	1 3/4" ○ (Pea)	3/4" ○	3/8" ○	3/4" - 0" 3/8" - 0"
The Foothills Collieries Ltd.		500	4" ○	2" □	1" □	1/2" □	0"
McLeod River Hard Coal Co.	McLeod River Mine	1000	5" ○	2 1/4" ○	1 5/8" □	3/8" □ ← (fines) →	0"
	Mercoal Mine	1000		2 1/2" ○	1 1/4" □	7/16" □	0"
McGillivray Creek Coal & Coke Co.		875	4" ○		1 1/4" □	3/8" ○	0"

○ indicates round screen holes

□ indicates square screen holes

Observations on the foregoing Tables

The observations on the foregoing tables are set out below so that they can readily be related to the observations which have already been made on the compilation of the questionnaire (p. 13 et. seq.)

Sub-bituminous Mines

Items 4 and 6

In no case is the coal from individual seams treated separately. The combined output is treated.

Item 5

The daily output of most of the mines is relatively low, approximating to only about 400 tons. There are, however, exceptions in which outputs rise to 1,000 tons per day. Considering the possibility of installing coal-cleaning plant, it is unfortunate that the completed questionnaires give no information on the ash contents of the marketed or discarded products.

If one may judge by experimental results obtained with a demonstration model of an Air-Sand Dry-Cleaning plant (described later, p. 38), dry cleaning, especially at the larger mines, appears to merit serious consideration.

A survey of the quality of the commercial products would also probably be worth while.

Item 7 and 8

The screening practice in the sub-bituminous mines is fairly uniform, (Table III), especially in the case of the larger sizes of coal.

Speaking generally, the sizes are:

Lump . . . . . over 4 in.
Egg. . . . . . 4 in. to 2 in.
Nut. . . . . . variable[*]
Stoker . . . . variable[**]
Slack. . . . . variable from 0-3/4 in. to 0-3/8 in.

The relatively large minimum size of coal for stoker use raises the important question as to whether it would not be profitable to recover and include in the stoker coal material down to 1/8 in. size i.e. material commonly spoken of as "buckwheat size". Apparently the market for slack is restricted, and slack may have to be actually discarded. Recovery of a buckwheat size and its inclusion in the stoker coal might then be worth consideration, provided, of course, that there is scope in the stoker coal market.

Item 9 and 10

The coal mined in the sub-bituminous field is in general very free from dust, so that naturally dust proofing is not practised. Except for three mines in which the coal is handpicked, and one mine in which it is said a calcium chloride treatment is adopted (for reasons not given), the coal which is mined is untreated except for sizing.

Item 11 and 12

The blocky nature of the coal as mined is apparently the reason

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[*] With regard to the variation in nut sizes, 8 mines prepare 1 inch to 2 inches, whilst at the remaining 8 mines, the sizes do not exceed 2 inches but the minimum size is variable.

[**] The variation in stoker sizes is from 1 inch to 1 1/2 inches as a maximum, to 3/8 inches to 3/4 inches as a minimum. The slack is material below the lower limits.

for the use of crushers at two mines and for the current installation of a crusher in a third mine. A fourth mine has a crusher but this apparently is not now used.

With the rather scanty information given, it is difficult to draw any specific conclusions under these items, but the subject of coal breakage is mentioned in one instance as a problem worthy of study and conceivably the distribution to the mines as a whole, of information on the efficiency of various types of breakers might be considered.

Item 13

It has already been pointed out under Items 9 and 10 that the only cleaning treatment mentioned in the returns was handpicking in three cases.

The fine coal is removed immediately prior to loading into railway cars. The screens used for the larger sizes are generally shaker screens, and in particular the Marcus screen is specified. For nut and stoker sizes, the use of wire mesh rotary screens is common practice, but four mines have vibrating screens installed. The Hummer screen seems to be favoured.

Item 14

Drying is not practised in the sub-bituminous mines.

Item 15 and 16

Since washing is not practised there were no returns under these items.

Item 17

The only problems for investigation which are mentioned, are cleaning and coal breakage.

Most of the returns make no comment under this item.

Bituminous Mines

Items 4 and 6

As is the case in the sub-bituminous mines coal from individual seams is combined before treatment.

Item 5

The daily output of the bituminous mines varies considerably, ranging from 120 tons in the smallest undertakings to 1500 - 1700 tons in the larger concerns, whilst the largest actually produces 4000 tons.

Naturally it is the larger concerns which have installed wet washing plants of which in all there are five and three of these in addition use dry cleaning. Dry cleaning plants are also installed at two further mines. Of a total daily output of over 17,000 tons from the bituminous mines making returns, approximately 12,500 tons are either cleaned by dry or wet methods. This represents 71 per cent.

Items 7 and 8 (See Table VI)

As with the sub-bituminous mines, a survey of commercial products is worthy of consideration.

In the bituminous mines a variety of screens are employed dependent upon the kind of treatment given to the run-of-mine coal and the particular sizes and quality of products marketed. These vary very considerably.

It will be seen from Table IV that a variety of screens are used, including bar screens, shaker screens, rotary screens (especially for the smaller sizes) and vibrating screens. As far as vibrating screens are concerned, the Hummer is favoured, but the Gyrex, Niagara and Ty-rock are named.

Screening practice in the bituminous mines varies somewhat from that in the sub-bituminous mines.

The size of the lump coal may be in excess of 4 inches, 5 inches or 6 inches, round hole or bar screen or oval hole with a minor axis of 8 inches. The other products vary in size. Egg may range from 1 1/8 inches to as much as 2 5/8 inches minimum size up to the undersize of the lump size. Similarly in the nut size, the minimum sizes range from 1 inch to 1 5/8 inches, with one concern making a product which is described as "pea" size, 1 3/4 inches to 3/4 inches.

Stoker sizes are equally variable with minimum sizes as low as 1/4 inches and maximum sizes up to 5/8 inches. Again one undertaking markets two qualities of stoker coal, one ranging from 1 1/8 inches to 5/8 inches and the other from 5/8 inches to 1/4 inches.

It is of interest to observe that some of the bituminous mines are including in their stoker size, material down to 1/6 inches, in view of the suggestion made earlier that the sub-bituminous should follow the same procedure.

With regard to the size of slacks, precise information in the returns is extremely scanty. If one can assume in most cases that all material below stoker size is included in the slack, then with one exception all the slack produced represents coal with a maximum size below the minimum size for stoker coal.

With regard to the exception, in this case a slack is produced from 1 1/8 inches to 0 inches in size.

It must be remembered, however, that very considerable qualities of bituminous coal are used for briquetting, and this represents material

below 1/4 inch.

The whole question of sizing in the coal mines of Alberta is one which would probably repay systematic examination.

Items 9 and 10

In contrast to the sub-bituminous coals the bituminous coals are in general of a dense character and presumably markedly so where folding of the seams has rendered the coal excessively friable.

Two undertakings have employed, or are employing, oil spraying. Another uses treatment with calcium chloride, and yet a fourth employs both oil spraying and calcium chloride treatment.

Items 11 and 12

Breakers are used in four of the mines and hand-operated breakers in another two.

Since the latter have together a daily output of 2000 tons, one would have thought that the installation of wholly mechanically operated breakers would have been profitable.

In view of what has already been said under sub-bituminous mines with regard to the economical breaking of coal, it is suggested that technical information on the subject would be of considerable interest to the operators.

Item 13

In the bituminous field (as far as can be gathered from the completed returns) in all, only five wet coal-washing plants are installed. Dry cleaning is employed in three of these instances along with wet washing, and alone in two other cases.

It is not possible to summarize the procedures employed for

the preparation of, and cleaning of the various products in all these cases, since for example, whereas at one mine employing dry cleaning, the material treated is between 3/16 inch and 1/2 inch, in a second case the size range is from 2 1/2 inches to 0. In the latter instance practically no detailed information is available. Coal of 2 1/2 inch size seems to be extraordinarily large for treatment in this way. In some cases the material is screened into suitable size ranges and treated over separate air tables.

Four of the washers mentioned are jig washers, and the fifth a dense medium plant which uses finely-divided limestone for making the medium.

As has already been noted, the returns do not state specifically what is the general practice with the finest coal, but whether this is marketed separately as slack, first mixed with other sizes and then marketed as slack, or briquetted, it may be stated that the ash content of such material is probably higher than that of the larger coal and its cleaning economically is a matter of the greatest importance to the coal operators.

Moreover, whilst one might assume that the wet-washing plants are operating at an efficiency which is considered most economical, this would not appear to be the case with all the dry-cleaning plants. Snap samples taken from air tables in operation at one of the mines showed that with these particular tables, the amount of cleaning was almost negligible. The ash content of the material passing to the tables was 17.5 per cent. and of the treated product was 17.2 per cent.

Item 14

In the bituminous field, in all, there are five drying plants. No details of the types of dryer are given.

Item 15

Information is given with respect to the treatment of coal slurries with regard to two coal washeries only. In the first instance the slurry is apparently simply settled and presumably mixed with the slack coal. In the second instance the slurry is treated by froth-flotation and the floated product dewatered in a Bird centrifuge. This treatment represents the best modern practice. No mention is made of the use of any flocculation agents.

Item 16

With regard to the nomenclature used for the marketed products, generally speaking the usual terms apply, but in addition, the word "slack" may receive some qualification. For example, a slack of large size may be called a 'pea' slack or a size may be marketed known as a "nut-pea". This latter grade is distinguished from steam coal in that it would not contain material less than 1/4 inch in size. A "furnace" coal may be marketed consisting of material of 1 1/2 inch to 6 inches, and the unusual term, 'sea' coal, is apparently used to describe coal dust. Coal briquettes are of course a common product of the bituminous mines, and a partially-washed run-of-mine coal is apparently produced, particularly to meet railway requirements.

The output from the bituminous mines appears to find a market principally as locomotive coal, but some is used for industrial and domestic purposes.

Item 17

Only two problems are mentioned in the completed returns, namely, the problem of separating bone coal in a cleaning process and the application of a dense medium process for this purpose, and also the freezing of fine coal.

The first appears to be simply a matter of the examination of particular samples of coal by coal-washing tests in the laboratory and the second, if of sufficiently wide importance, requires more extended examination than is possible in this survey.

Summary

A survey of coal preparation practices in the coal mines of the Province of Alberta has been carried out by means of a questionnaire compiled with a view to elucidating the salient features of the present situation.

Unfortunately, the number of completed questionnaires returned was small, but examination of the information obtained has allowed of certain important conclusions being drawn and it has been possible to suggest further enquiries which might be made to improve the present practice.

PART II

STUDIES IN FUNDAMENTALS RELATING TO THE CLEANING OF FINE COAL.

PART II

STUDIES IN FUNDAMENTALS RELATING TO THE CLEANING OF FINE COAL

Introduction

As the preparation of coal has developed, there has been an increasing tendency to separate out the fine coal and to regard it as an end product. The difficulties associated with the occurrence of fine coal in the operation of wet-washing processes often necessitate the additional use of a froth-flotation process and were later largely responsible for the increasing introduction of air-cleaning tables into coal preparation practice. Fine coal is difficult to utilise since it usually has a high ash content, it may be irregular in quality, it is difficult to transport and its very fineness excludes its use in many types of coal burning equipment.

As the mechanisation of coal mining has increased, the quantity of fine coal produced has likewise increased. As indicating the quantity of fine coal which has to be dealt with, the statement of M. K. Burrows ([3]) may be quoted, that in Britain the annual production of material passing a 1/8 inch screen is about 25 million tons.

In Alberta, the proportion of the total output of coal, passing a 1/8 inch screen may be larger than in Britain especially

if one considers only the output of the bituminous mines. The friable nature of the seams in the bituminous areas has already been referred to, whilst considerable quantities of fines are produced from the sub-bituminous coals on storage. The overriding importance of satisfactory methods for cleaning this material prior either to utilizing it as fine material or briquetting it before use, will therefore be appreciated.

Scope of Experimental Work

The studies described hereafter were commenced with a view to elucidating some of the principles which apply in certain coal cleaning processes designed for treating small coal and in particular a process which has been described for the recovery of fine coal from coal slurries produced in wet-washing processes (vide infra.)

The Stephens-Adamson Air Sand Cleaning Process

During the course of carrying out fundamental work in the laboratory, a demonstration model of a plant operated on principles closely related to those being studied, was loaned to the Research Council of Alberta. This plant is known as the Stephen's-Adamson Air-Sand Cleaning Plant.

(a) Description of Plant

A photograph of the model is shown in Figure 2 and a diagrammatic sketch of the full scale plant is given in Figure 3. The essential part of the plant is the launder type separator through which the sand flows at a relatively rapid rate, the flow being induced by the launder being inclined at an angle of 5° to the horizontal and being given a reciprocating motion. The floor of the separator consists of three porous alundum plates through which air can pass upward to be released in fine bubbles uniformly over the bottom of the separator from three windboxes provided beneath it.

Two vertical shale chutes are provided in the floor of the separator, one after the first porous plate and the other between the second and third plates. Fine, washed silica sand, suitably graded, is delivered continuously to the upper end of the separator from a storage hopper, the flow being regulated by a gate.

As it passes through the box, it is aerated and fluidised by the air passing through the porous plates, to a degree which presumably, when the model was working efficiently, could be varied as required by altering the setting of controlling air valves below the air boxes. Most of the sand travels the whole length of the

Figure 2

MODEL OF STEPHEN'S-ADAMSON AIR-SAND CLEANING PLANT.

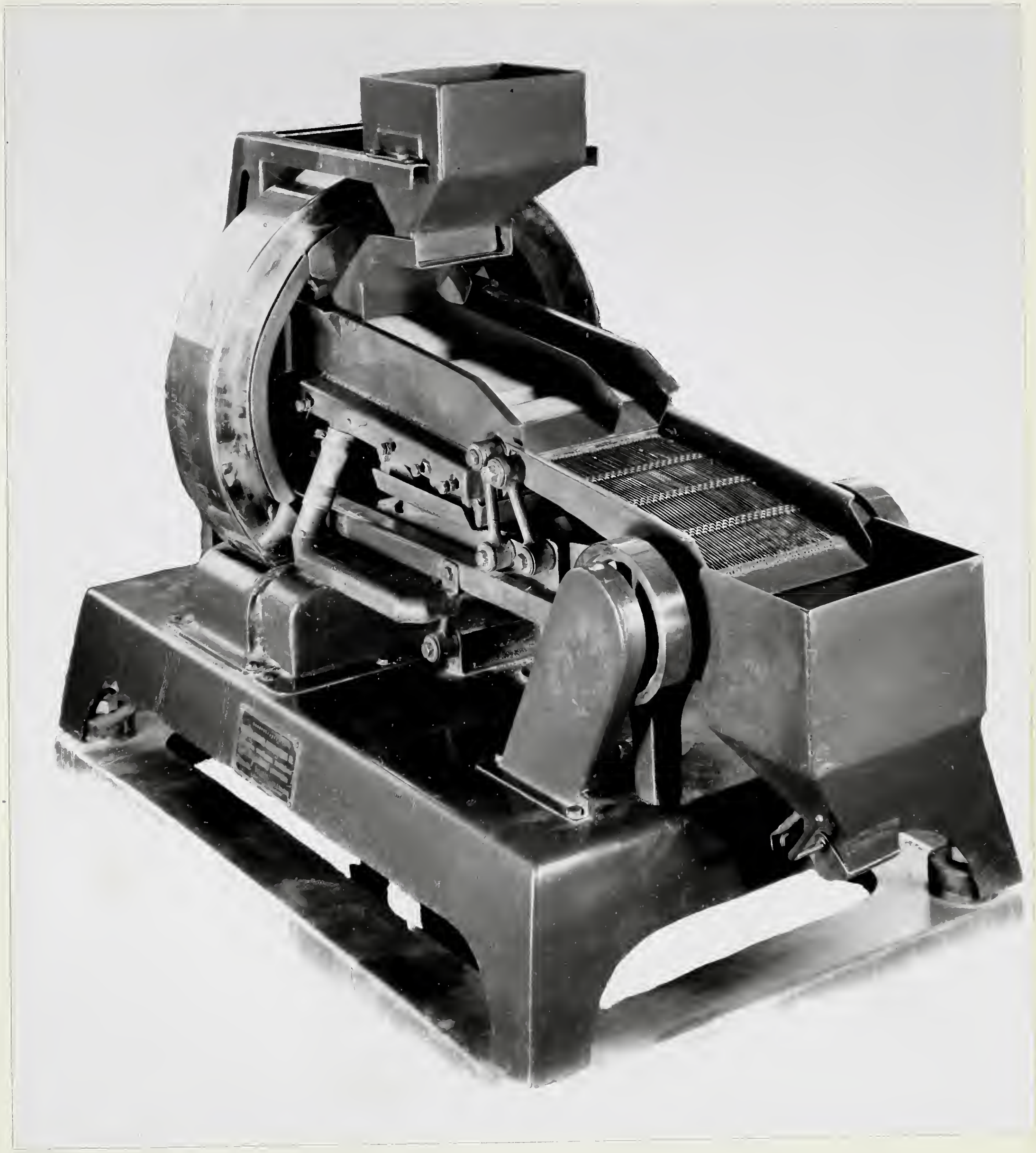
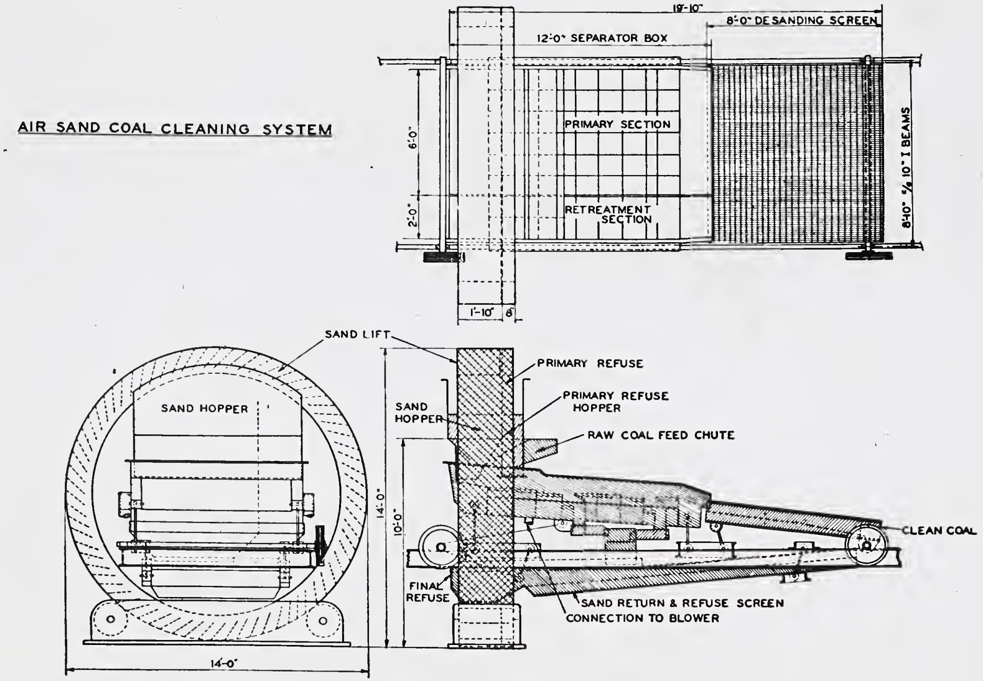


Figure 3

DIAGRAM OF STEPHEN'S-ADAMSON AIR-SAND CLEANING PLANT.



Six-Foot Air-Sand Separator

separator and discharges onto a de-sanding screen for return to the sand hopper.

The quantity of sand passing through the two shale chutes can be controlled by adjustable gates at the chute outlets.

(b) Experimental Conditions of Operation of Model Plant

With the model in question, mechanical defects made it impossible to obtain a uniformly aerated sand bed. Also the small size of the machine placed severe limitations on the quantity of coal which could be tested. The value of the results obtained was limited accordingly.

The maximum size of coal which could be used on the model was stated to be 3/4 inch. Trial runs, however, using 3/4 inch - 3/8 inch sized material caused frequent interruption of operatins owing to the largest pieces blocking the feed and recovery chutes, and in the experiments described later, material of 3/8 inch - 3/16 inch was employed.

As the coal passes through the separator, the dirty coal and shale, according to the respective densities, find their way through the fluidised bed of sand. In a large scale plant, by suitable adjustment, principally shaley material can be discharged through the first shale chute, the second shale chute serving to discharge a "middling" product, i.e. coaly shale. In the model, however, the rejected material from both chutes was combined and

later passed over desanding screens.

Experimentally, this material was recirculated and any portion of it which was recovered as coal was added to that obtained in the first treatment.

With the quantities of coal which could be recovered from the apparatus, it was not possible to obtain a sample truly representative of the bulk with the size of coal which had to be used in the model. These tests however suffice to show that the principles of operation were satisfactory and the experiments were only discontinued because adjustment of the fluidity of the bed was not possible.

(c) Experimental Results

Two samples of coal were tested, one of the sub-bituminous type and the other of the bituminous type.

(1) Treatment of Sub-bituminous Coal

A sample of sub-bituminous coal was obtained from the Black Diamond Mine of the Great West Coal Company.

Two and one half Kilograms of coal, sized between $\frac{1}{2}$ inch and $\frac{1}{4}$ inch was submitted to laboratory sink-and-float tests. The results are given in Table VII

TABLE VII

Laboratory Sink and Float Tests on Black Diamond Sub-bituminous Coal

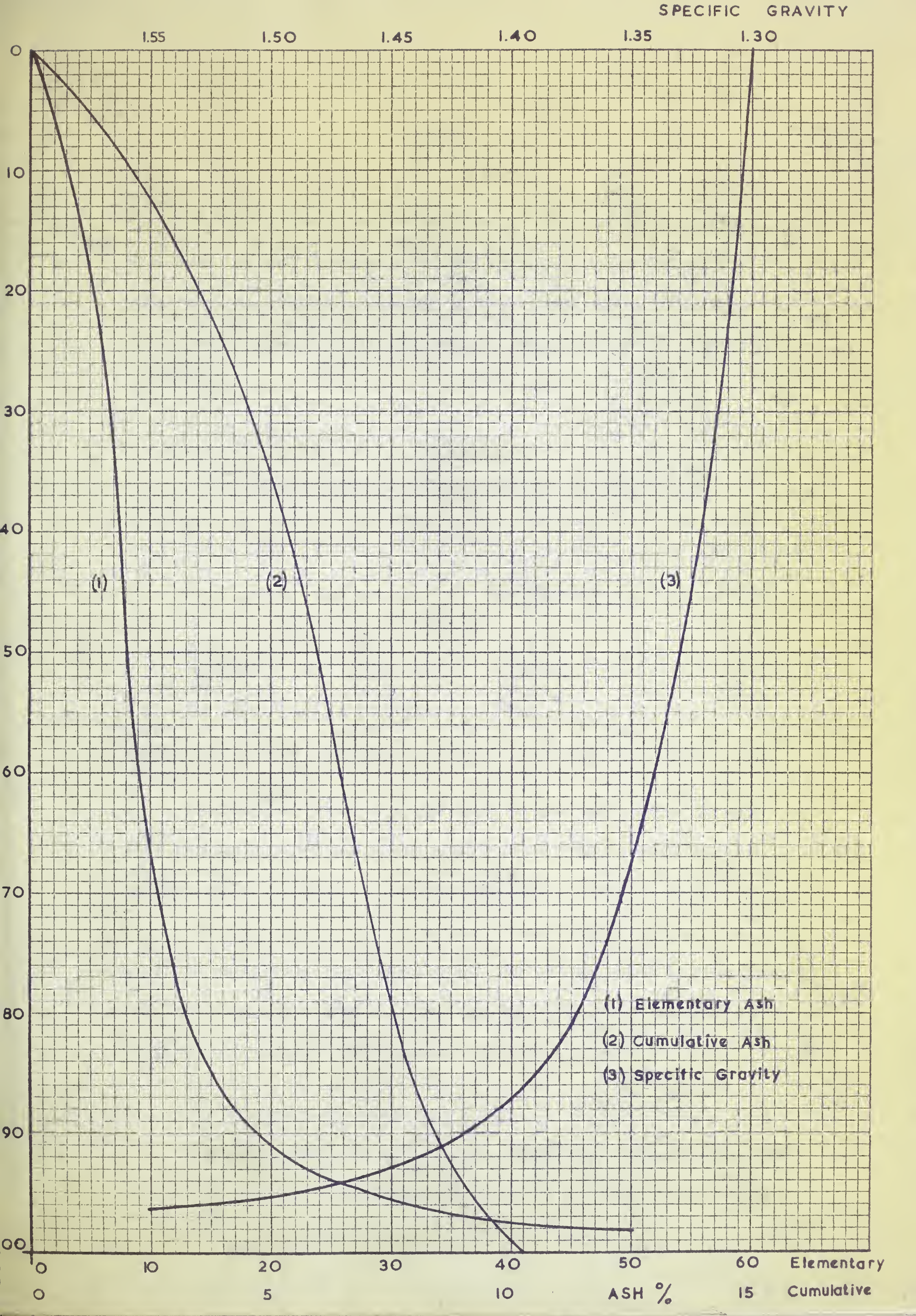
Sp. Gr.	Yield of floated Material %	Cumulative Yield of floated Material %	Ash %	Cumulative Ash of floated Material %
1.30	0	0	0	0
1.35	67.7	67.7	6.9	6.9
1.40	19.7	87.4	11.9	8.1
1.45	5.5	92.9	18.5	8.7
1.50	2.2	95.1	25.4	9.0
1.55	1.2	96.3	30.4	9.3
Sinking at 1.55	3.7	100.0	50.5	10.8
	100.0			

The data given in Table VII is shown graphically in Figure 4. Runs were then made on the Air-Sand Model, employing in each case 1200-1400 grams of material of the same size using in turn a deep and a shallow sand bed in the separator.

The shallow sand bed was approximately $\frac{1}{4}$ inch in depth and the deep sand bed, obtained by fixing a sand-weir at the exit end of the separator, was approximately $\frac{1}{2}$ inch in depth.

Figure 4

WASHABILITY CURVES FOR COAL FROM
THE BLACK DIAMOND MINE OF THE
GREAT WEST COAL CO. LTD.


SPECIFIC GRAVITY
1.55
1.50
1.45
1.40
1.35
1.30
0
10
20
30
40
50
60
70
80
90
100
(1)
(2)
(3)
(1) Elementary Ash
(2) Cumulative Ash
(3) Specific Gravity
0
10
20
30
40
50
60
Elementary
0
5
10
ASH %
15
Cumulative

Two separate sets of runs were made, the first using a slow rate of feed for the raw coal, and the second with a fast rate of feed. The ash contents of the recovered coal and the reject were determined in every case. The results are shown in Table VIII.

TABLE VIII

Cleaning of Sub-bituminous Coal on Air-Sand Model

Run	Type of Bed	Product Yield %	Product Ash %		Reject Ash %
			Theoretical	Actual	Actual
1	Deep	95.7	9.2	8.4	79.5
2	Shallow	95.6	9.2	9.5	71.9
3 *	Deep	96.5	9.4	9.8	81.2
4 *	Shallow	96.4	9.4	9.9	74.2

*Runs 3 and 4 were made using a faster feed rate for the raw coal.

The results given in Table VIII in one case appear to show that a product can be obtained with a lower ash content than is theoretically possible as indicated by the results in Table VII.

This case apart, the results in Table VIII indicate that material of relatively high ash content can be separated by this process and a clean product obtained approaching in ash content and yield that obtained in laboratory washability tests.

(2) Treatment of Bituminous Coal

A sample of 100 lbs of bituminous coal was obtained from the Lethbridge Collieries Ltd. As received, it contained considerable

surface moisture and was approximately of 2 inch size.

The sample was air-dried and then broken in a jaw crusher to a maximum size of 3/4 inch.

Chronologically this was the first sample examined in the Air-Sand model and laboratory washability tests were made on the assumption that the model would handle material up to 3/4" inch size as stated above. The coal had to be ground to smaller size before treatment in the model, so that comparison of results obtained in the laboratory with those obtained with the model is not strictly valid. The results of the laboratory washability tests are given in Table IX.

TABLE IX

Laboratory Sink and Float Tests on Lethbridge Coal

Sp. Gr.	Yield of Floated Material Percent	Cumulative Yield of floated Material Percent	Ash Perc.	Cumulative Ash of floated Material Percent
1.30	0.2	0.2	2.5	2.5
1.35	61.4	61.6	6.5	6.5
1.40	22.9	84.5	10.8	7.7
1.45	7.3	91.8	17.0	8.4
1.50	2.9	94.7	23.8	8.9
1.55	0.9	95.6	28.8	9.1
Sinking at 1.55	4.4	100.0	48.6	10.8 *
	100.0			

*Separate determination of the ash content of the bulk material gave 10.7 percent.

The results in Table IX are shown graphically in Figure 5.

For the runs on the Model, 500 - 600 grams of material of 3/8 inch - 3/16 inch size were employed. As with the sub-bituminous coal, two series of runs were made using alternately a shallow and a deep bed.

The results obtained are shown in Table X.

TABLE X

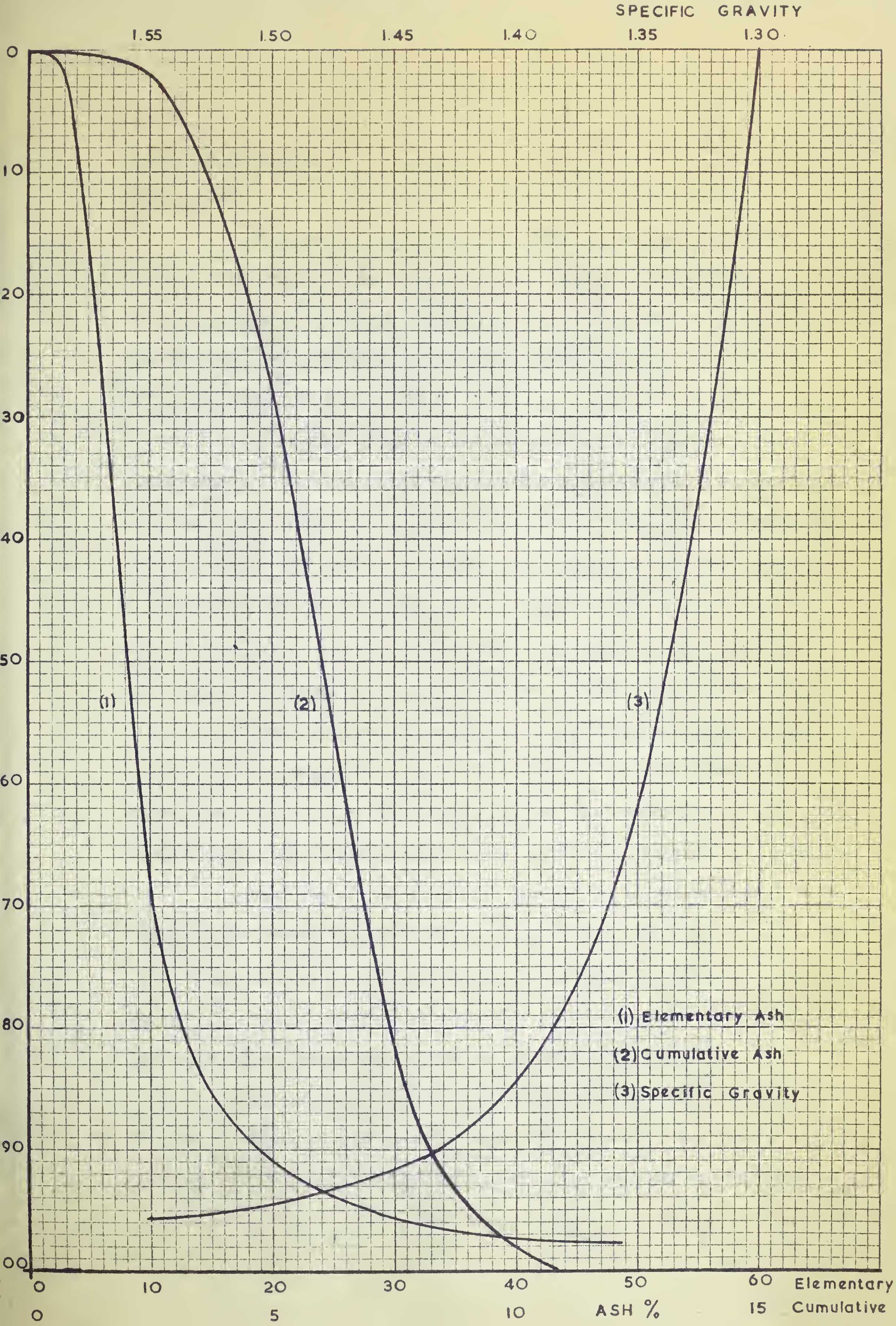
Cleaning of Bituminous Coal on Air-Sand Model

Run	Type of Bed	Product Yield %	Product Ash % Theoretical	Product Ash % Actual	Reject Ash % Actual
1	Shallow	95.5	9.1	9.3	40.8
2	Shallow	94.4	8.8	9.0	41.1
3	Deep	96.8	9.4	8.8	56.2
4	Deep	91.2	8.3	9.0	38.3

In one case given in Table X, a product is shown as obtainable with the model, which has a lower ash content than the theoretical. In this case also, the percentage product yield is the lowest. As with the sub-bituminous coals, the results show the separation of a reject material of relatively high ash content and a clean product approaching in ash content and yield, that obtained in washability tests.

Figure 5

WASHABILITY CURVES FOR COAL FROM
THE LETHBRIDGE COLLIERIES LTD.


SPECIFIC GRAVITY
1.55
1.50
1.45
1.40
1.35
1.30
0
10
20
30
40
50
60
70
80
90
00
(1)
(2)
(3)
(1) Elementary Ash
(2) Cumulative Ash
(3) Specific Gravity
0
10
20
30
40
50
60
Elementary
0
5
10
ASH %
15
Cumulative

Fundamental Studies

Introduction

Particular mention has been made of the Barvoys Dense Medium Wet Washing process (Part I p. 6) and the Air-Sand Dry Cleaning process (p.38) as illustrating modern processes of coal cleaning, which, although the processes differ greatly in design, yet operate on like principles.

An aerated sand bed can, of course, be regarded as a dense medium. The principles of operation of dense medium plants (and the same might be said of the principles concerning hindered settling) are but little understood. Quoting, for example, L. W. Needham and S. Lynch in a paper on "The Use of Suspensions as Heavy Liquids" (^{4}), "the fundamentals of the properties of suspensions of this type are by no means fully understood. The subject is one (like so many) in which for a time practice leads theory, but a stage is reached where further development waits on a proper appreciation of fundamental principles. For this reason any work which can be done on solid/ water systems, generally, is extremely valuable."

A search of the extensive literature which has been published in recent years directed attention in particular to a paper by L. Andrews on the "Recovery of Fine Coal from Washery Slimes" (^{5}), which gives an account of preliminary investigations leading to the development of the so-called Sy-Vor process.

Referring to this process amongst others, A. Grounds and W. Reed (^{6}) speak of the need for intensive research into the cleaning of fine coal. Since the experimental work to be described

later originated in a study of the above paper by L. Andrews, a short account is given of the appropriate features of this paper.

L. Andrews' Experiments

Two distinct aspects of the problem were considered, namely the cleaning of fine coal between 1/16 inch and 1/200 inch, and the cleaning of material below 1/200 inch. It was considered that cleaning of material below 1/200 inch could only be satisfactorily achieved by froth flotation. Following observations made during previous experiments on the separation of metalliferous ores of varying specific gravity, L. Andrews carried out a preliminary investigation on samples of clean coal of specific gravity 1.4 and samples of quartz sand screened respectively to between 20 mesh and 30 mesh size (mean diameter 0.028 inches) and to between 80 and 100 mesh size (mean diameter 0.006 inches). The free falling velocities in water of the several samples were determined by noting the time taken for particles of each grade of material to fall through a 4 foot column of clean, still water contained in a 1 inch diameter glass tube.

Particles of the 0.028 inch size coal fell at a rate of 8 ft./min. and those of 0.006 inch sand at a rate of 4 ft./min.

Since the free-falling velocity of the sand was half that of the coal particles, and since the specific gravity of the coal was 1.4 and that of the sand was 2.65, it ~~will be obvious~~ may be shown that the particles of sand and coal could not be separated by normal classification methods.

To investigate the possibility of separation by a dense

medium, a portion of the coal was allowed to settle at the bottom of a narrow cylindrical container of water, and a suitable quantity of the sand settled carefully on top of it.

A tube passing to the bottom of the coal bed made possible the passing of an upward stream of water through the combined bed. Below a certain minimum flow, the water simply percolated through the whole bed, but above this rate, provided that the rate of water flow was not too high, the whole bed expanded and particles of sand found their way to the bottom of the container so that in time the sand displaced the coal, and the position of the sand and coal beds were reversed. At low rates of flow the separation of coal and sand at the top of the sand bed was perfectly clean. At higher rates of flow, separation became ill-defined, and when the rates of flow increased still further, the separation of the coal and sand entirely disappeared, particles of coal falling to the bottom and rising to the top of the entire bed. At this stage, the velocity of flow was still considerably less than the free-falling velocities of the sand or the coal, so that water flowing out of the beaker was quite clear and the height of the mixed bed remained substantially constant. Apart from showing that the head required to make water flow through a particular suspension, fitted the accepted formula governing the formation of quicksand beds, as quoted in soils mechanics texts, L. Andrews did not proceed to make a fundamental study of this, as a method of separation.

The formula to which Andrews refers is:

$$P = \frac{L \times (S - p)}{1 + e}$$

where P = downward pressure of solid opposing water flow

L = height of solid-liquid column

S = specific gravity of solid particles

p = specific gravity of fluid

e = ratio of water volume to solid volume

It should be noted that the size of particle does not enter into the formula.

Conditions in a Sand Bed

At the outset it is essential that the different physical states of a sand bed in experiments of this kind should be clearly defined and named. Although these states were not so well understood in the earliest experiments, an account of which is given later, it is thought desirable to introduce definitions at this stage.

When water is passed at an increasing rate through a bed of uniformly sized sand resting, as in these experiments, on a permeable medium, at first no change in the condition of the bed is perceptible. As the rate of flow of water increases, the bed expands and later commences to "teeter", or as it were, to boil. Ultimately a rate of flow may be attained at which particles of sand travel freely with the stream.

Three states may be defined:-

(a) Consolidated state

In this state, the bed has the maximum packing density. In early experiments the necessity for tapping the tube to attain this condition prior to taking measurements, was not recognized.

This definition, however, is given here since it is thought desirable to use the same terms throughout.

(b) Expanded state

It has not been possible in any apparatus used, to observe exactly the flow, when a consolidated bed starts to expand. Under the conditions used, even with most careful measurements, the commencement of the change from the consolidated to the expanded state could not be clearly perceived. The bed, in the early stages of expansion, retained its appearance of consolidation and here the differentiation appears to be simply a matter of precision of measurement.

Expansion continues until each particle is free to move with respect to its neighbouring particles. Until this stage is reached, the free movement of a particle may be restricted by neighbouring particles. This state ceases and passes into a third state as soon as the bed has expanded to a degree where free movement of particles is possible. The third state is known as the "teetering state."

(c) Teetering State (Fluidised State)

It is difficult to say precisely what is the degree of freedom of movement of an individual particle in the early stages of this state. For purposes of definition, the state is considered as the teetering state as soon as each particle is removed from contact

with neighbouring particles and is completely free to move in the fluid medium. In brief, the state is analogous to a suspension, except that in this case the state of suspension is only maintained by the upward flowing stream of fluid.

This condition continues, with individual particles becoming separated by greater distances from each other, until the rate of flow of fluid exceeds the settling velocity of the particles. Ideally, if the particles were perfect spheres, presumably they would remain stationary in the fluid. In fact, however, due to such factors as irregularities of particle shape, this condition can never be attained. The term "teetering" thus really defines a condition in which the particles are in a free localized movement.

Experimentally, channelling occurs and accordingly currents are set up in the bed which may be compared with convection currents, and the bed has thus the appearance of boiling. This occurrence makes difficult, precise measurement of the length of a teetering bed, especially in the initial phases. As the flow increases still further, whilst the bed is still in the teetering condition, these "convection" effects diminish.

The teetering condition ceases when the velocity of the fluid exceeds the settling velocity of the individual particles. At this stage the particles are carried upward with the stream.

Design of Apparatus and Initial Experiments

In the course of the experimental work to be described, several designs of apparatus were used. At the commencement of the work considerable difficulties were encountered owing to tubes of suitable length and diameter not being available, and to the lack of facilities for constructing apparatus.

Nature of Sand Used

The only sand available was a sample of Ottawa Sand. This was screened exhaustively into the following fractions, using standard Tyler screens:

Grade	Mesh Size
Coarse	20 - 28
Medium	28- 48
Fine	48 - 65

Material over 20 mesh and less than 65 mesh was discarded. These separate fractions were used throughout the whole of the experimental work.

Apparatus No. 1.

The first apparatus is shown in Figure 6. It was manufactured entirely in the laboratory. The main flow tube, A, was constructed by fusing together two pieces of glass tubing of about

Figure 6

DIAGRAM OF APPARATUS NO. I.

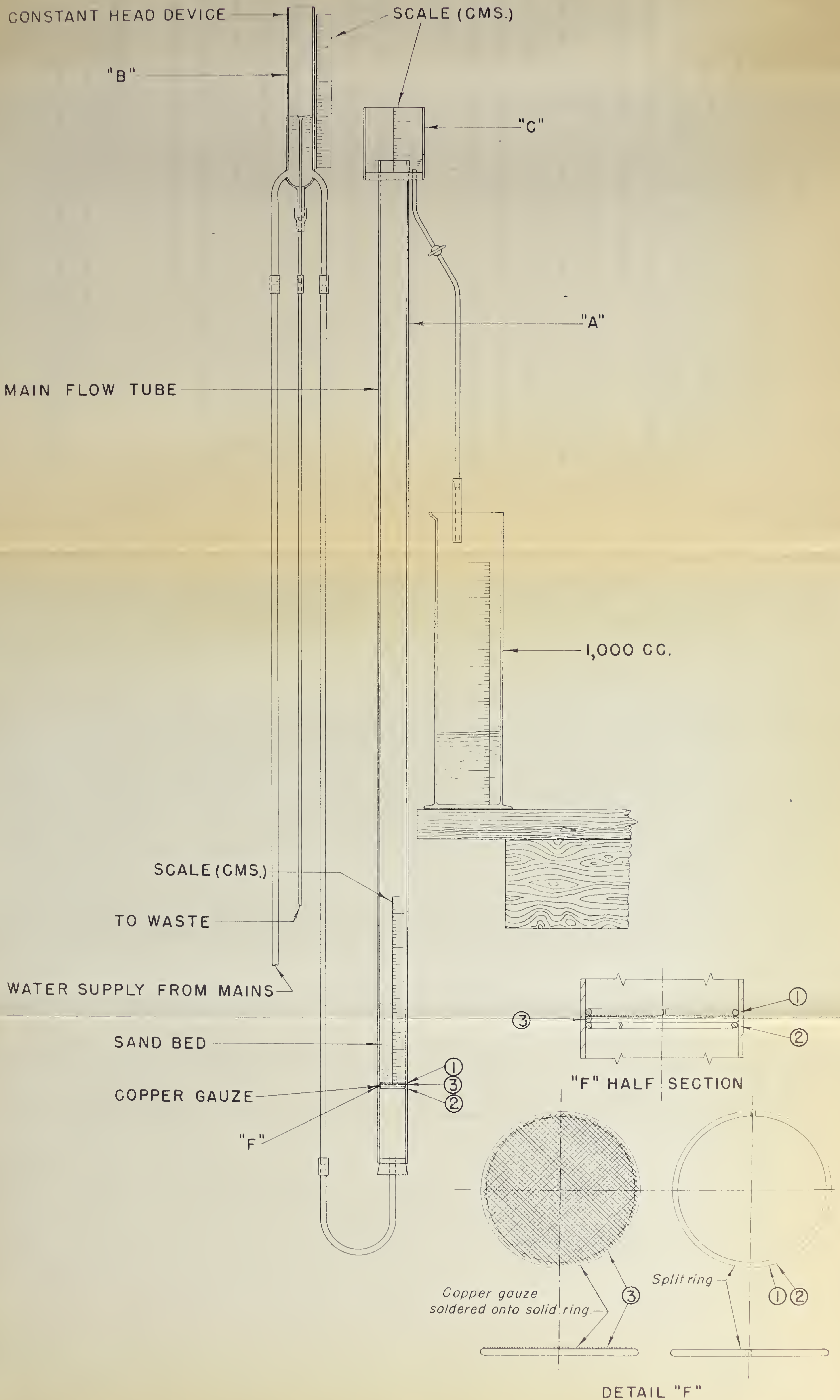


FIGURE 6
APPARATUS No. I.

3 ft. in length and of 1 3/4 inches in diameter. The bed of solid was supported in this tube on a disc F. cut from a piece of 200 mesh copper gauze. The copper gauze was fixed as firmly as possible between two wire split rings shaped to fit the inside of the tube, as shown in detail in Figure 6.

A constant level reservoir, C, was fitted to the top of the main flow tube by means of a large cork shive. The constant head device, B, was of conventional design with the central tube adjustable so that the constant head could be varied as desired. Water flowing from the exit tube of the reservoir was collected and measured.

After filling the apparatus with water, a suitable quantity of the fine sand was introduced into the main flow tube forming a bed supported on the wire gauze.

The depth of the bed, without water flow, was then measured. Then water was passed through the main flow tube and as the flow of water was increased the bed expanded and expansion continued until, if a sufficiently high rate of flow could have been attained, particles of sand would presumably have been carried out of the tube into the constant level tank.

Tests With Apparatus No. 1.

The weight of sand in the bed was 155.5 g.

The rates of flow ranged from zero to 3000 ml./min. The

rates of flow were measured by collecting a measured volume of the effluent water in a calibrated cylinder over a known period of time.

At each rate of flow, the depth of the bed was measured in cms. by means of a scale fixed to the side of the main flow tube. When the bed was in the consolidated or the expanded state, these measurements were reasonably accurate, but when teetering commenced the bed was so disturbed by "convection" currents that the surface was very uneven and variable, and anything approaching precise measurement was impossible.

The water used was taken directly from the mains. The temperature of the water was measured by a thermometer placed in the water-collecting vessel.

In this thesis the following nomenclature is used throughout:

L = depth of the bed in the consolidated, expanded or teetering condition. (cms.)

ΔH = differential head of water as measured between the level of water in the constant level tank, A, and the level of water in the constant head device, B, (cms.)

V = volume of water collected (ml.)

t = time for collection of water (sec.)

Q = rate of flow of water. (mls/sec.)

ρ_f = density of fluid medium (g./ml.)

ρs = density of material composing the bed (g./ml.)

Δ = effective density of the system, e.g. the density of suspension of sand in water. (g/ml.)

μ = viscosity of fluid (lb./ft. sec.)

D_p = mean diameter of particle (ins.)

u_m = linear velocity of fluid flow in empty tube (ft/sec)

W = mass flow of fluid (lb/sec)

ϵ = ~~percentage~~ fractional free space in bed

u_t = velocity of free falling particle in still fluid (ft/sec.)

u_i = fluid velocity in interstices of bed (ft/sec.)

Re_m = modified Reynolds Number based on condition in empty tube, (dimensionless)

F = viscous drag to which particles are subjected (ft.lbs/sec^2)

TABLE XI

Temp. °C	Depth of Bed L cms.	Differential Head ΔH cms.	Volume Received V mls.	Time for flow of V mls. secs.	Rate of Flow Q mls/sec.	Rmks.
16	7.5	4.5	300	153	2.0	
	7.5	6.8	500	176	2.9	
	8.0	7.45	500	101	5.0	
	8.1	8.5	600	94	6.4	
	8.3	9.4	800	80	10.0	Uneven teetering commenced.
	9.5	14.5	800	46	17.4	
	11.2	19.6	1000	44	22.0	
	20.7	34.2	1000	24	42.0	
	23.5	37.5	1000	22	45.5	

Figures 7 and 8 have been prepared from the results in Table XI. Figure 7 expresses the relationship between the head (ΔH cms.) against the volume of water collected (Q ml/sec.).

When Figure 7 was originally plotted, it was thought that one curve might reasonably be drawn from the origin of the axes representing a mean of all the points as shown in Figure 7. Later experiments demonstrated that when the bed expands, the curve changes in direction and form. If the curve representing conditions in the expanded state is drawn as in Figure 7, this would represent a linear relationship between the variables, a conclusion which later experiments show to be incorrect.

It should be noted that the points falling within this region could equally well be represented by a curve. Similarly, the first two points and the origin might be considered to fall on a straight line, which again is in accordance with the results of later experiments.

Figure 8 shows the relationship between the depth of bed, L in cms., with flow, Q, in mls/sec. This graph is also confirmed by the results of later experiments. It shows more clearly the rate of flow at which the change occurs in the bed from the consolidated to the expanded state.

At this stage it was concluded that the apparatus was unsatisfactory and required modification, especially in view of the disturbed nature of the bed leading to a very uneven surface. Moreover it was almost impossible to control the head reasonably accurately.

Figure 7

GRAPH SHOWING THE RELATIONSHIP BETWEEN PRESSURE DROP AND RATE OF FLOW OF FLUID.

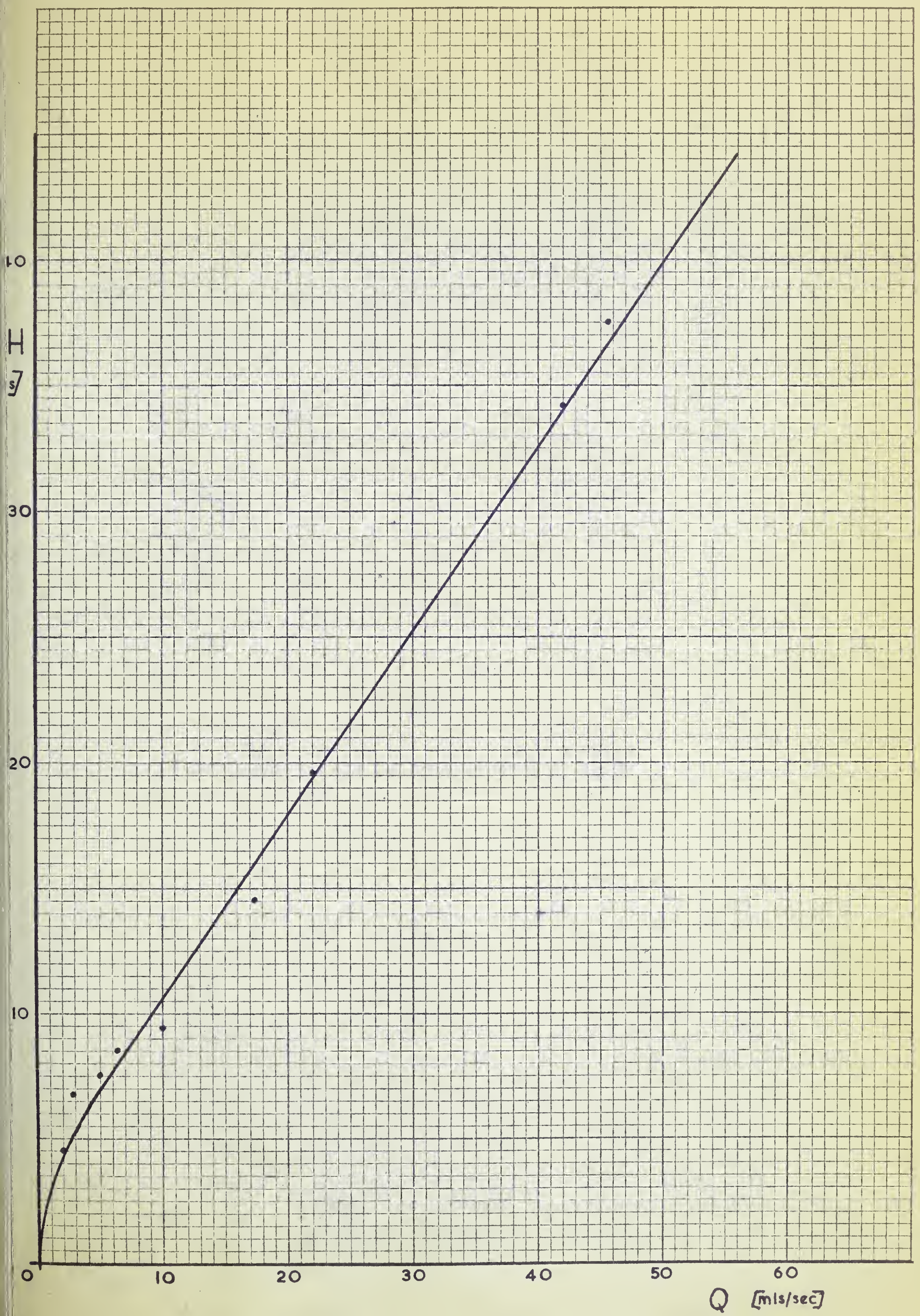
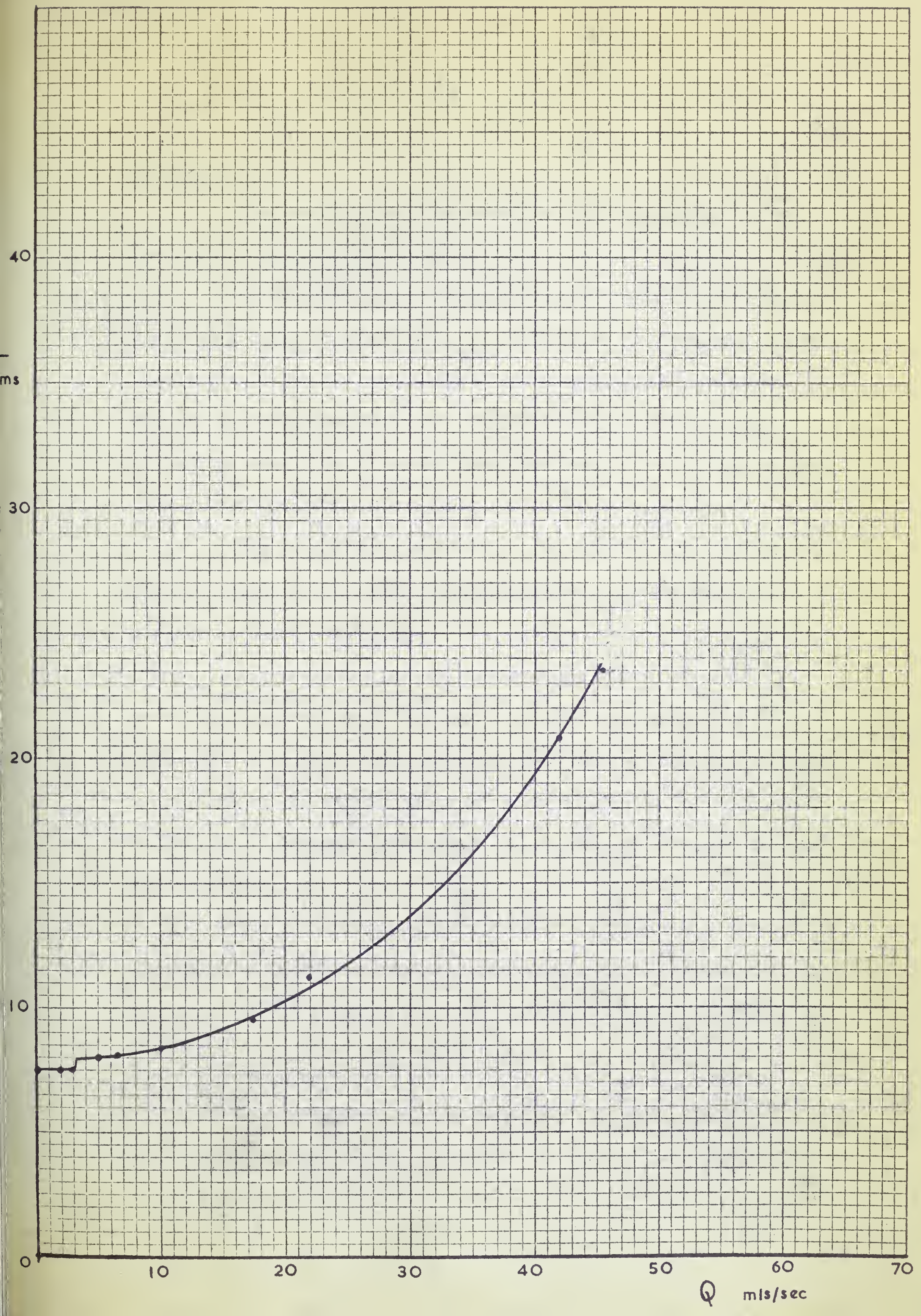

30
20
10
H
s]
0
10
20
30
40
50
60
Q [mls/sec]

Figure 8

GRAPH SHOWING THE RELATIONSHIP BETWEEN DEPTH OF BED AND RATE OF FLOW OF FLUID.


40
ms
30
20
10
0
10
20
30
40
50
60
70
Q mls/sec

Apparatus No. 2

The modifications introduced in this apparatus can be seen by reference to Figure 9.

The principal modification was the replacement of the gauze by a sintered glass disc, C, in the hope that thereby better conditions in the bed would result and accordingly more precise control would be possible. It should be pointed out that the second apparatus, owing to the immediate shortage of supplies, must be regarded purely as constructed for temporary purposes.

The reason for introducing the water through a central tube, F, was that the only sintered glass plate available was already in this form.

The provision of the siphon tube, D, and the tube, E, made for easier and more accurate control of the flow. The only difficulty with this arrangement was that occasionally an air bubble would form at the highest point of the outlet tube, D. This could be removed by temporarily passing a rapid current of water through the apparatus.

The sintered glass plate proved efficient in reducing disturbances in the sand bed and accordingly apparatus No. 3 was designed and arrangements made for its construction and supply.

Tests with Apparatus No. 2

Measurements were made using the temporary apparatus. Table XII is given as indicating the nature of the results obtained with this apparatus.

Figure 9

DIAGRAM OF APPARATUS NO.2.

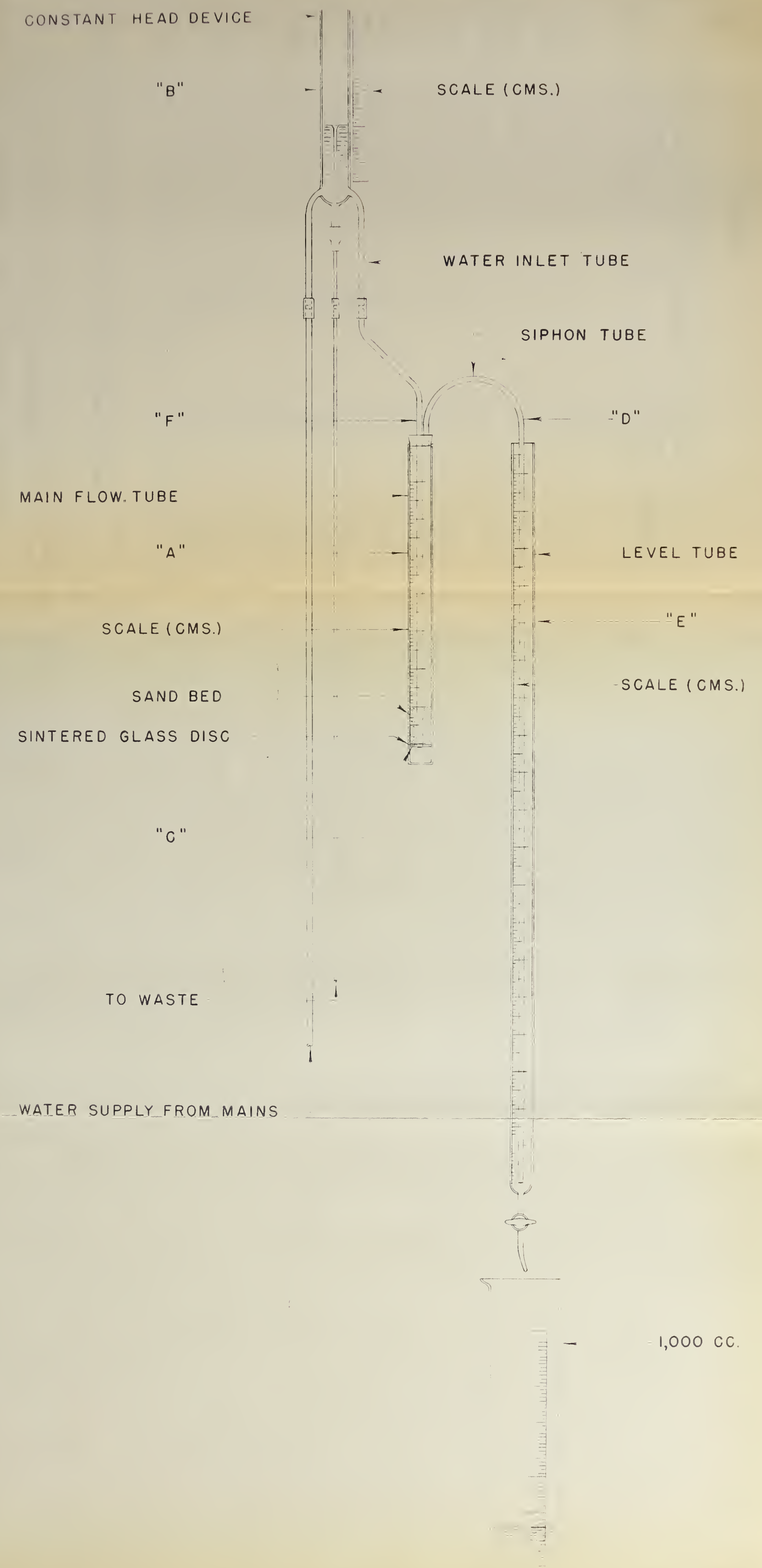


FIGURE 9
APPARATUS No. 2

Table XII

Fine Sand used

Temp. °C	Depth of bed L cms.	Differential Head Δ H cms.	Volume Measured V mls.	Time for flow of V mls sec.s	Rate of flow Q mls/sec.
19	7.0	0	0	0	0
	6.95	6.7	100	208	0.5
	6.95	12.0	100	110	0.9
	6.9	17.8	100	72	1.4
	6.95	22.0	100	63	1.6
	7.15	24.7	250	128	2.0
	7.3	26.8	250	109	2.3
	7.55	30.9	350	122	2.9
	7.9	34.7	350	136	3.7
	8.1	37.4	350	88	4.0
	8.25	39.5	350	80	4.4
	8.5	42.3	350	72	4.9
	8.75	44.3	350	67	5.2
	8.9	46.3	350	64	5.5

The appropriate data in Table XII are shown in Figure 10 and Figure 11.

In Figure 10, the distinction between the consolidated and expanded conditions is more pronounced. It will be seen from Figure 10 that

Figure 10

GRAPH SHOWING THE RELATIONSHIP BETWEEN
PRESSURE DROP AND RATE OF FLOW OF FLUID.

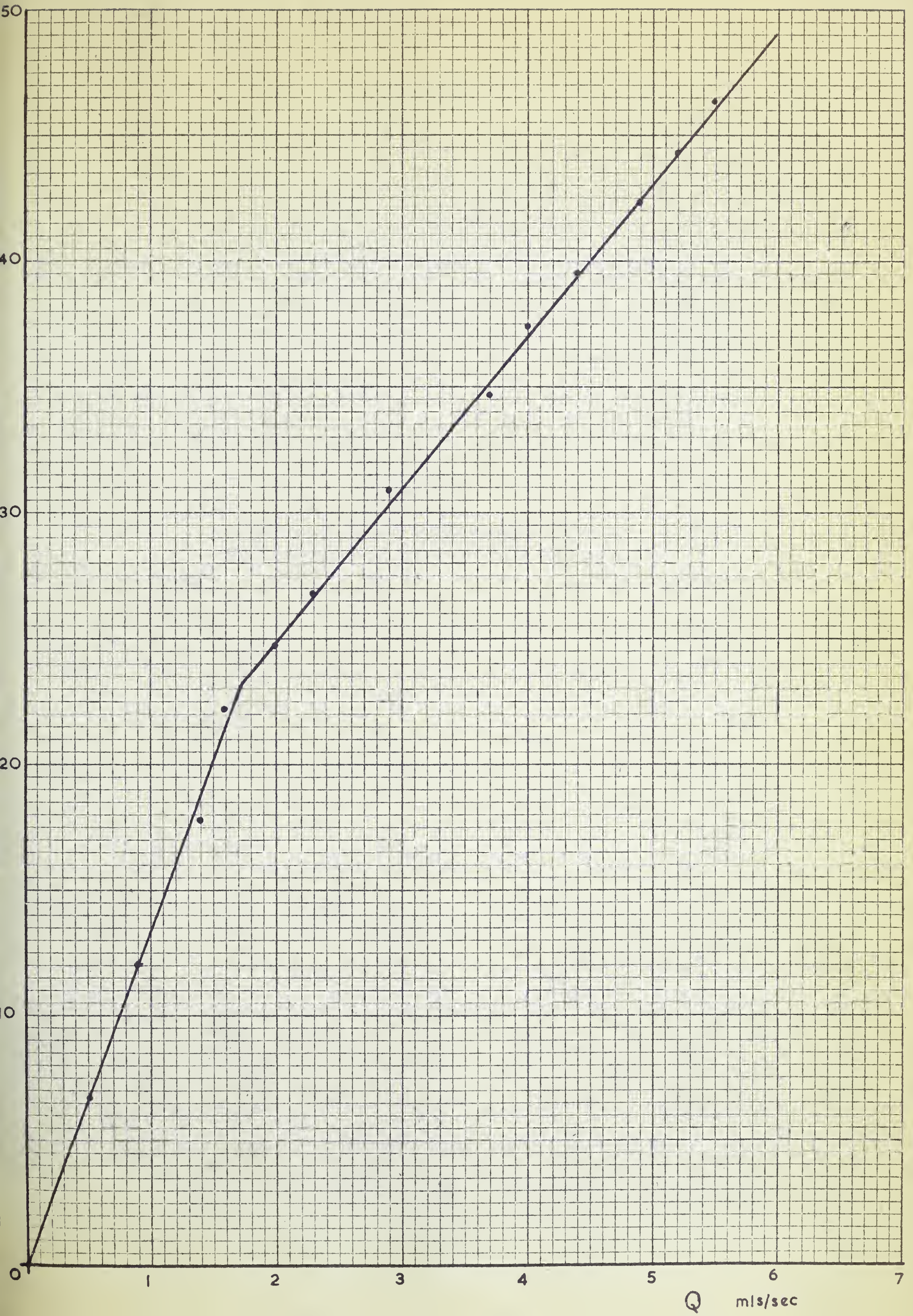
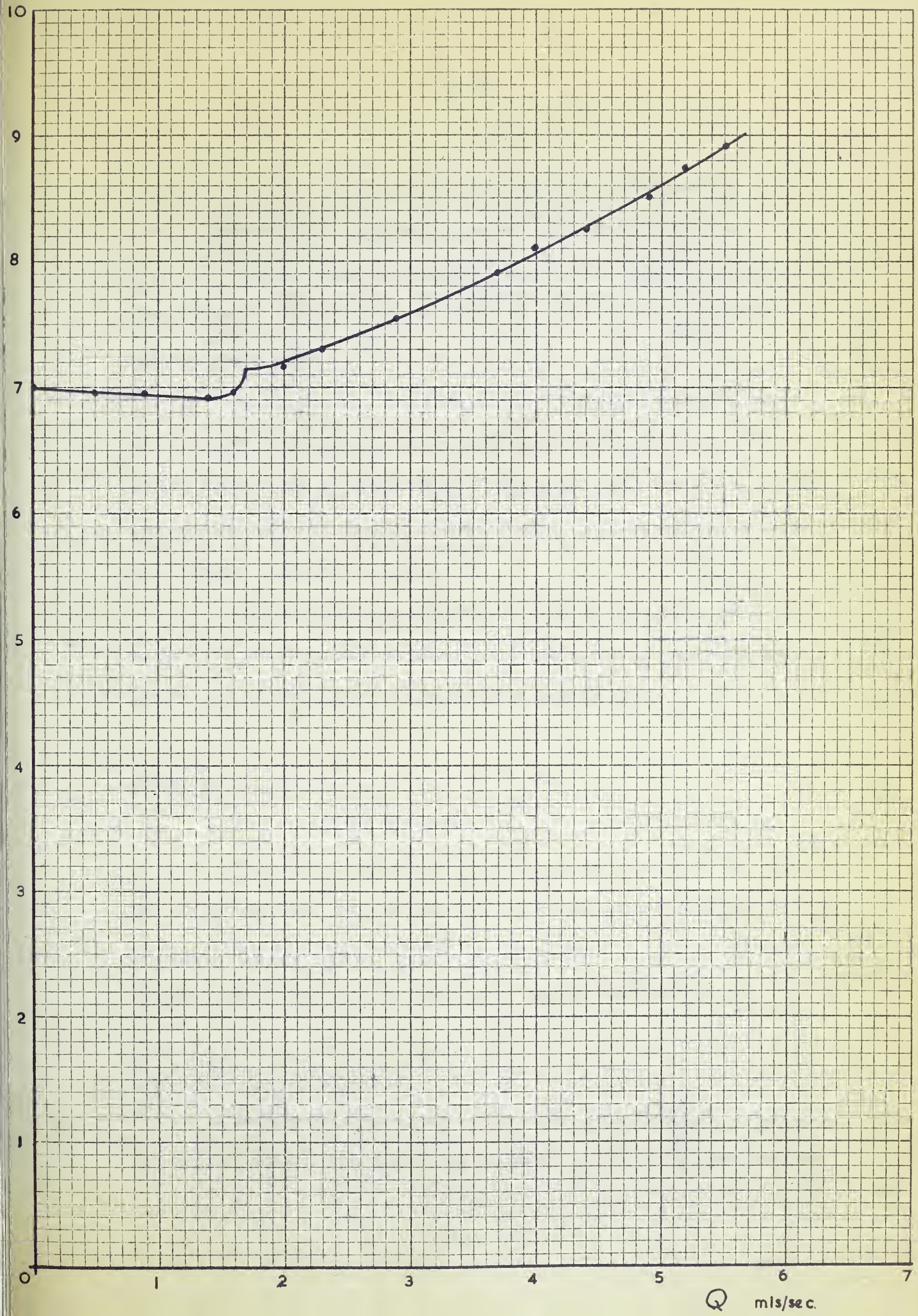

50
40
30
20
10
0
0
1
2
3
4
5
6
7
Q m/s/sec

Figure 11

GRAPH SHOWING THE RELATIONSHIP BETWEEN DEPTH OF BED AND RATE OF FLOW OF FLUID.


10
9
8
7
6
5
4
3
2
1
0
1
2
3
4
5
6
7
Q mls/sec.

the first position of the curve is a straight line passing through the origin. The points on the remaining portion of the curve appear to be best fitted by a straight line, but as already noted with respect to Figure 7, this view is incorrect as will be shown later.

In Figure 11, the step showing the change from a consolidated to an expanded bed is not as marked as in Figure 8. Within the limits of adjustment of the apparatus, the change from a consolidated to an expanded bed is quite sudden, as represented by the steps in Figures 8 and 11.

The very high resistance to flow of this apparatus, due to the use of the sintered glass plate in place of the wire mesh support is brought out clearly by this comparison.

Apparatus No. 3

The design of Apparatus No. 3 is shown in Figure 12.

This was essentially the same as apparatus No. 2, with the exception that the central inlet tube was dispensed with and provision was made for an inlet in the form of a conical portion. The sintered glass disc was actually sealed in position.

Tests with Apparatus No. 3

Before attempting any measurements of sand bed resistance, the measurement of the free flow of water through the apparatus was

Figure 12

DIAGRAM OF APPARATUS NO.3.

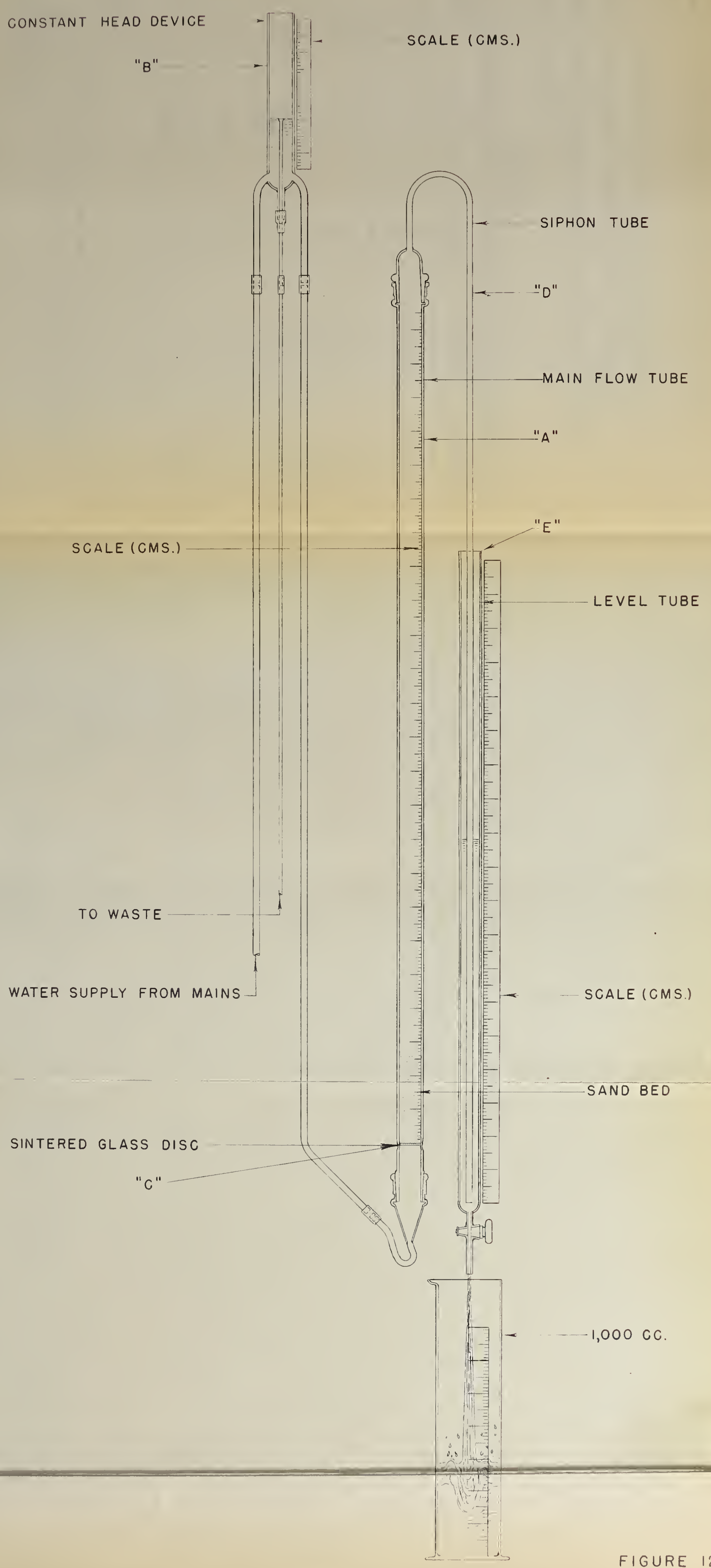


FIGURE 12
APPARATUS No. 3.

commenced. The differential head could be measured to within 0.5 mm.

After experience had been gained in the use of the apparatus, measurements of variations of flow, at arbitrarily selected values for the head of water, were made with the results shown in Table XIII

Table XIII

Temp. °C	Depth of bed L cms.	Differential Head ΔH cms.	Volume Measured V mls.	Time for flow of V mls. secs.	Rate of flow Q mls/sec.
21		18.4	100	68	1.47
		41.6	250	74	3.38
		79.1	500	80	6.25
		102.6	500	63	7.95
		8.0	100	151	0.663
		32.1	100	38	2.64
		51.5	250	61	4.1
		73.3	250	43	5.8
		92.7	500	68	7.35
		109.6	500	59	8.5

A duplicate run with conditions precisely the same as in the previous case, made after a short time interval, gave the results shown in Table XIV.

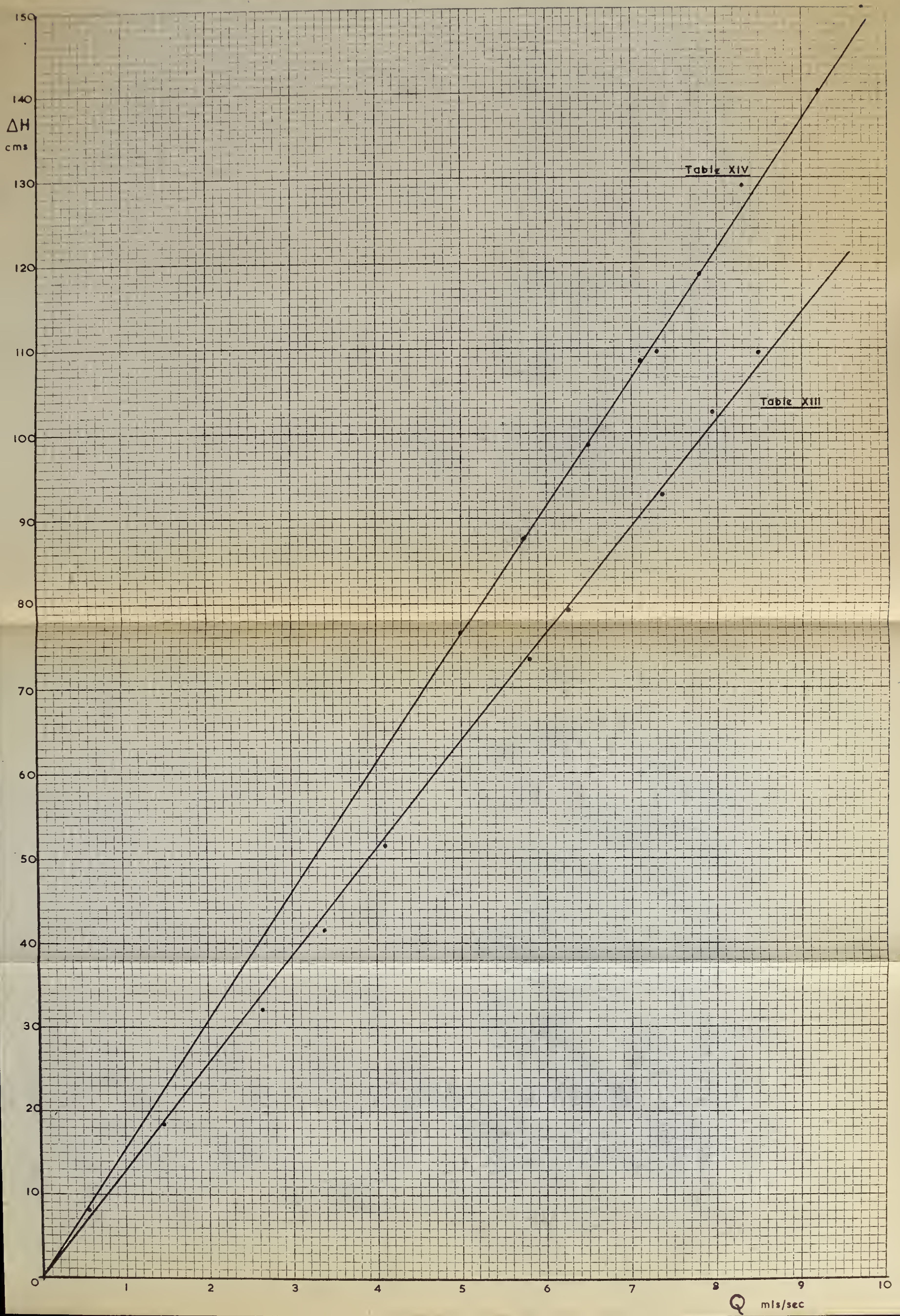
TABLE XIV

Temp. °C	Depth of bed L cms.	Differential Head ΔH cms.	Volume Measured V mls.	Time for flow of V mls. sec.	Rate of flow Q mls/sec.
19		109.5	1000	137	7.3
		76.3	500	100	5.0
		87.7	500	87	5.75
		98.8	500	77	6.5
		108.4	500	70	7.1
		118.6	500	64	7.8
		129.0	500	60	8.3
		140.3	1000	109	9.2
		150.1	1000	103	9.7
		160.0	1000	98	10.2
		168.5	1000	94	10.7
		154.9	1000	90	11.1
		178.8	1000	87	11.5

When the results shown in Tables XIII and XIV were graphed (Figure 13), it was obvious that the resistance to flow had increased with the lapse of time. This result was so unexpected that a number of repeat determinations were made, which only served to confirm that as the length of time of use of the apparatus increased, so did its resistance. It has not been thought necessary

Figure 13

GRAPH SHOWING RELATIONSHIP BETWEEN PRESSURE DROP AND RATE OF FLOW OF FLUID FROM TABLES XIII AND XIV.


ΔH
cms
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
1
2
3
4
5
6
7
8
9
10
Q mls/sec
Table XIV
Table XIII

to give the detailed readings, since Tables XIII and XIV suffice to indicate the nature of the difference obtained on repeating the experimental run. The location of the increase in resistance appeared obviously to be the sintered glass plate, and accordingly this plate was given treatment with moderately concentrated nitric acid in the hope that any deposit lodging there would be removed. To test the effectiveness of this treatment a further set of readings were made. Since it is thought desirable to include the data on which the resultant curve is based, the actual results obtained are given in Table XV and shown in Figure 14.

Table XV

Temp. °C	Depth of bed L cms.	Differential Head ΔH cms.	Volume Measured V mls.	Time for flow of V mls. sec.	Rate of flow Q mls/sec.
19		174.3	1000	60	16.67
		110.9	1000	92	10.9
		72.3	1000	143	7.0
		150.4	1000	71	14.1

It will be seen from Figure 14 that this treatment reduced the resistance substantially. It appeared clear therefore that probably material was collecting in the interstices of the plate. It was thought

Figure 14

GRAPH SHOWING RELATIONSHIP BETWEEN
PRESSURE DROP AND RATE OF FLOW OF
FLUID FROM TABLES XV TO XVII.

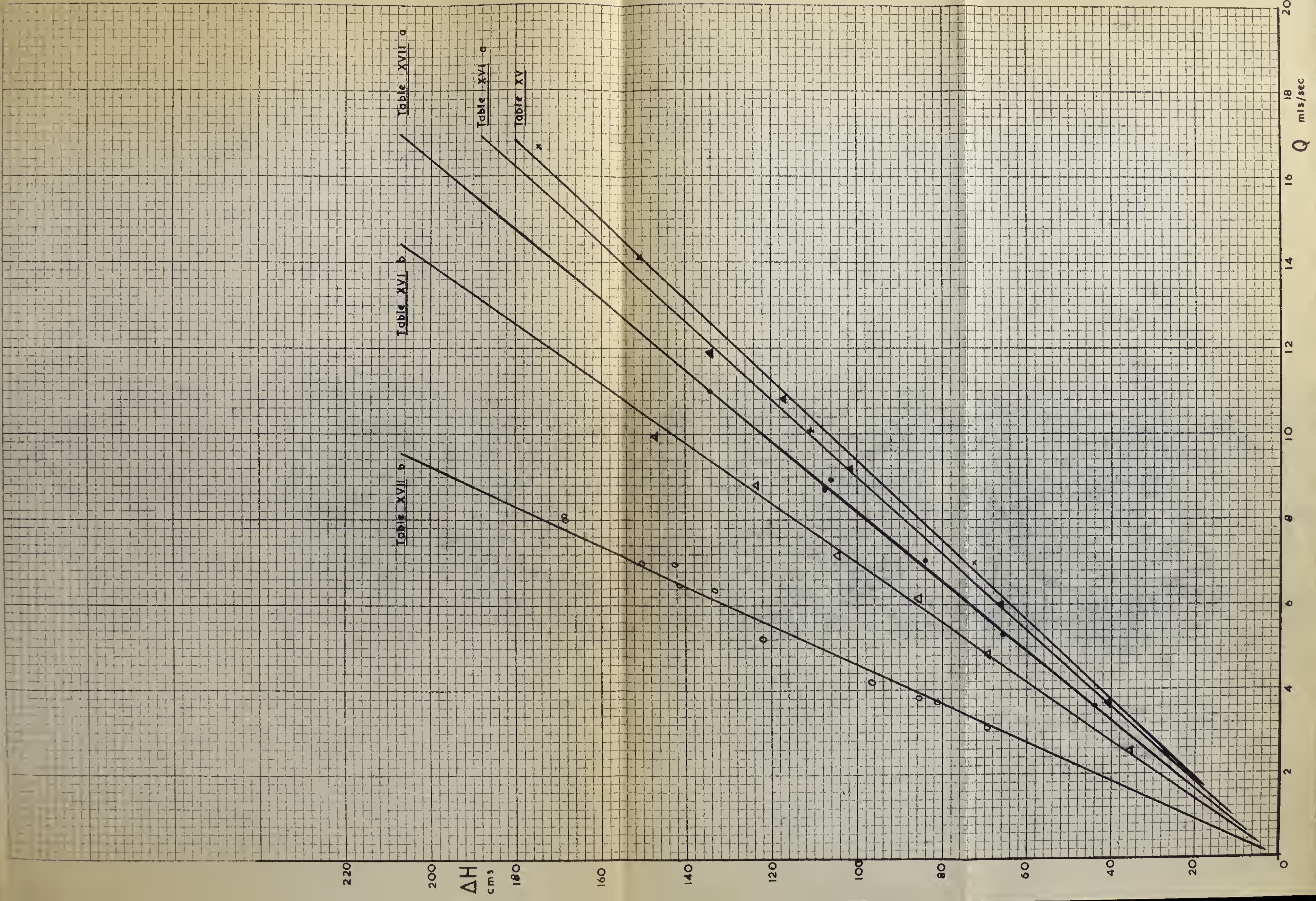


Table XVII a
Table XVI a
Table XV
Table XVI b
Table XVII b
ΔH
cms
0
20
40
60
80
100
120
140
160
180
200
220
Q
mls/sec
0
2
4
6
8
10
12
14
16
18
20

possible that the water being normal Edmonton mains water, and since it was known that this water receives considerable chemical treatment before distribution, that small particles of solid material might be being filtered out by the sintered glass plate. Accordingly a finer sintered glass plate filter was placed in the water feed line and the apparatus again tested. Results characteristic of the condition then obtaining are shown in Table XVI and Figure 14. It will be seen that the resistance of the apparatus still continued to increase with use.

TABLE XVI

Temp. °C	Depth of bed L cms.	Differential Head Δ H Cms	Volume Measured V mls.	Time for flow of V mls. sec.	Rate of flow Q mls/sec	Rmks.
20		41.1	500	137	3.65	Run (a) First run with water filter.
		66.5	500	84	6.0	
		102.1	1000	109	9.2	
		117.5	1000	93	10.8	
		134.2	1000	84	11.9	
		36.1	500	196	2.55	Run (b) Second run with water filter aft water had flowed for 3 hours.
		69.3	500	103	4.86	
		86.0	500	81	6.17	
		104.9	1000	139	7.19	
		123.8	1000	114	8.77	
		147.2	1000	101	9.90	

It thus seemed clear that the increasing resistance could not be due to very finely divided and not readily observable suspended matter in the water. In order to determine whether the resistance in the glass plate was increasing when there was no flow of water through it, the apparatus was allowed to stand for a considerable time. Immediately afterwards a reading was taken of the flow with the head fixed to correspond with a known point on the graph representing conditions of head which just preceded the period of standing.

In the course of a series of resistance measurements, if a repeat determination was made of the flow at any particular head with only a small period of time intervening, a substantially identical reading was obtained. If, however, having made a series of flow readings at regularly increasing heads, an attempt was made to repeat these readings, commencing with low rates of flow and going once more through the whole range of readings, an increase in resistance of the apparatus was invariably found. In such a case, an interval of say two hours at least would have elapsed between a reading at any particular head and the repeat determination of the same head. During a two-hour period of continuous experiment, a relatively large volume of water passed through the apparatus.

When the apparatus had stood without any flow of water over a long period and a repeat measurement was made, with a head selected from a series

of measurements carried out immediately preceding the standover period, since no volume of water had flowed through the apparatus in this case, one might have anticipated that the former reading would be substantially duplicated. This, however, was not found to be the case. To quote a typical instance, (for this procedure was repeated a number of times) whereas with a head of 68.0 cms. before the standover period the flow was 6.0 ml/sec., after a standover period of 8.4 hours with the same head, the flow was 5.58 ml/sec.

The only possible explanation which could be advanced for this state of affairs was that organisms were actually growing within the plate, so that the resistance increased as the apparatus was allowed to stand. Accordingly, as a last resort, it was decided to use distilled water instead of mains water. This was done by incorporating a pump in the system and using a closed circuit.

Table XVII and the curve on Figure 14 show that this arrangement effected no improvement whatever, and repeat experiments demonstrated a continued drift in the results.

Table XVII

o.	Depth of bed L cms.	Differential Head ΔH cms.	Volume Measured V mls.	Time of flow of V mls. sec.	Rate of flow Q mls/sec.	Remarks
		44.1	500	139	3.60	Run (a) First run using distilld water
		65.7	500	95	5.27	
		84.0	1000	142	7.04	
		106.1	1000	112	8.90	
		107.7	1000	115	8.70	
		134.0	1000	90	11.10	
		69.4	500	163	3.07	Run (b) Second run using distilld water, after allowing the apparatus an d water to stand for 60 hrs.
		80.6	500	135	3.71	
		85.6	500	133	3.76	
		96.4	500	118	4.24	
		121.9	500	96	5.21	
		133.2	500	78	6.41	
		140.9	500	77	6.49	
		142.8	500	72	6.95	
		150.0	500	72	6.95	
		168.6	500	63	8.00	
		169.1	500	62	8.06	

At this stage it was decided that this apparatus could not be used. It has been suggested that the drift in this appartus was probably due to the release of dissolved gas from mains water in its passage through the glass disc. This view does not seem to be supported by the results of the experiments described above.

Apparatus No. 4

Apparently the only alternative remaining, was to return to the use of a wire gauze as a support for the sand bed.

In order to overcome the difficulty of sealing this satisfactorily in the main flow tube, the use of glass was discarded and Lucite used in its place for constructing a new apparatus.

The Lucite tubing was of $3\frac{1}{2}$" bore and 4 ft. 4 in. in length.

A length of 6 inches was cut from one end of this tube, and a piece of gauze 'F' then sealed in between the short length and the remainder of the tube, using as a jointing material a thick solution of Lucite in chloroform.

To minimize disturbance from the incoming water from below the gauze, the inlet tube was directed downwards within the main flow tube. It will be seen from Figure 15 that otherwise the arrangement was substantially as in Figure 12.

Experimental runs made with this apparatus without a sand bed, gave excellent duplication of results.

Figure 15

DIAGRAM OF APPARATUS NO.4.

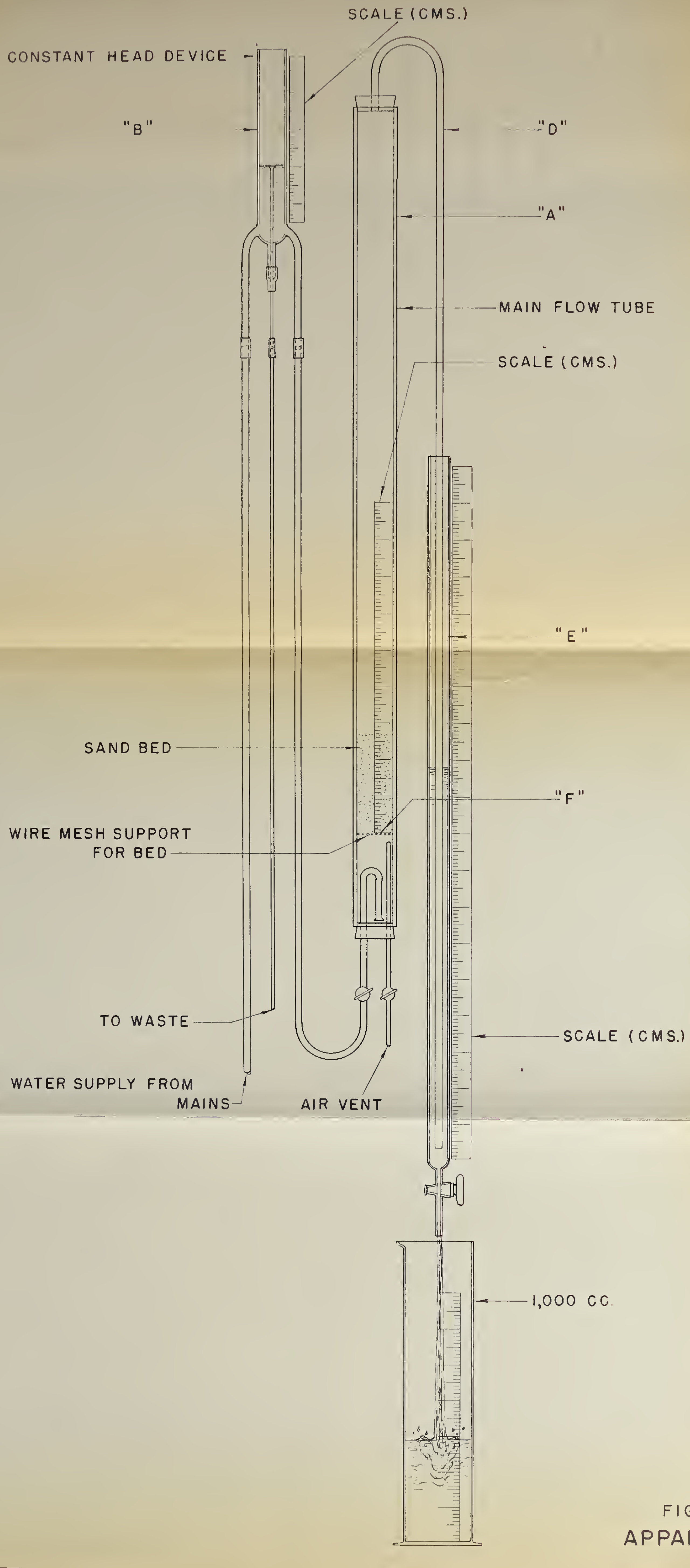


FIGURE 15
APPARATUS No. 4.

Standardisation of Apparatus

If the resistance of any bed of material alone in the apparatus is to be measured, it is necessary to know the flow characteristics of the apparatus in the absence of a bed. Knowing the resistance of the apparatus over the whole range of flow from measurements of head and flow taken when a bed of material is used, suitable quantities can be deducted to obtain the resistance of the bed of material alone.

Accordingly, after the satisfactory performance of the apparatus had been established, several runs were made with the apparatus without a bed of material for standardisation purposes.

Readings of head were taken to 0.5 mm. Readings of flow were taken to a fixed volume and timed to 0.2 second.

Table XVIII gives the average results for the head, ΔH, and the flow, Q, derived from a number of determinations with the apparatus without a bed.

TABLE XVIII

Temp. °C	Depth of bed L cms.	Differential Head ΔH cms.	Volume Measured V mls.	Time of flow of V mls. sec.	Rate of flow Q mls/sec.
18		1.4	1000	134.0	7.5
		4.7	1000	60.0	16.7
		10.4	1000	40.0	25.0
		14.2	5500	178.8	30.8
		15.7	1000	31.8	31.5
		20.9	1000	26.8	37.3
		23.4	5500	135.0	40.7
		26.2	1000	24.0	41.7
		33.4	5500	110.6	49.8
		41.7	5500	98.0	56.1
		47.4	5500	98.2	56.0
		51.2	6500	102.0	64.0
		60.3	7000	101.0	69.3
		60.4	5500	86.8	63.4
		68.0	7000	95.0	73.7
		71.1	5500	79.0	69.6
		80.8	5500	73.0	75.4
		83.0	8000	96.6	83.0
		91.1	5500	68.6	80.2
		94.1	8000	89.4	89.0
		103.1	9000	95.8	94.0
		104.8	5500	62.8	87.6
		115.8	5500	59.6	92.3
		124.8	5500	57.0	96.6

Experiments with Standardized Apparatus

In a study of flow conditions through a bed of particulate material, That is, a bed consisting of particles, the following are obvious factors:

(a) depth of bed

(b) diameter of bed

(c) particle size

(d) the shape of the particle

(e) particle density

(f) fluid density

(g) fluid viscosity

(h) particle roughness

(i) fluid velocity.

Having established the flow characteristics of the apparatus without a bed of material, series of experiments were carried out, with various known sizes of sand, in order to study the effect of increasing the depth of bed.

The sizes of sand used were those described previously as fine, medium and coarse. (p. 56).

The experiments are arranged to show the effect of increasing the depth of the bed using in turn the different sizes of sand.

(a) Experiments with Ottawa Sand

Series S.1.

In this series the finest size sand was used.

Table XIX

Depth of bed = 9.4 cms.

Temperature of water at inlet = 18 °C

Depth of bed L cms.	Differential Head Δ H cms.	Volume Measured V mls.	Time of flow of V mls. secs.	Rate of flow Q mls/sec.
9.4	--	--	--	--
9.6	8.1	500	238	2.1
10.5	10.1	500	46.8	10.7
16.2	19.5	500	19.2	26.0
22.0	29.3	6000	161.0	37.2
29.4	39.8	5500	117	46.7
32.5	47.1 *	8500	171.6	49.6
40.1	50.4	6000	108.6	55.3
41.3	56.6 *	7000	125.0	56.0
54.3	66.8 *	7000	111.4	61.4
56.8	60.6	8000	135.0	63.0
71.5	75.9 *	7500	109.6	68.4
95.0	85.5	8500	65.4	73.7

Table XX

Depth of bed - 17.7 cms.

Temperature - 18.0 °C

Depth of bed L cms.	Differential Head ΔH cms.	Volume Measured V mls	Time of flow of V mls. secs.	Rate of flow Q mls/sec.
17.7	-	-	-	-
17.9	8.5	375	362.2	1.04
17.9	14.0	500	258.0	1.9
19.7	16.5	500	66.8	7.5
29.0	25.1	500	21.2	23.6
38.2	31.6	5500	176.2	31.6
50.6	41.9	5500	169.8	42.4
65.4	50.9	6500	129.8	50.1
86.5	60.3	7000	123.2	56.9
101	64.8	6000	99.8	60.1

Table XXI

Depth of bed - 24.0 cms.

Temperature - 19 °C

Depth of bed L cms.	Differential Head ΔH cms	Volume Measured V mls	Time of flow of V mls. secs.	Rate of flow Q mls/sec.
24.0	-	-	-	-
24.0	16.5	400	237.8	1.7
25.5	20.8	500	81.2	6.2
43.7	31.5	500	21.0	23.8
58.8	41.5	5500	154.2	35.7
82.0	54.0	5500	116.4	47.3
109.5	64.7	5500	98.6	55.8

The values for ΔH and Q are plotted in Figure 16 for the three separate depths of bed. With the length of flow tube available it was not possible to exceed the initial depth of bed shown in Table XXI. Also in the same graph, a curve is constructed showing the relationship of ΔH and Q for the tube without a sand bed.

This curve and also the upper part of that plotted from the results shown in Table XIX, consist of two portions (a) and (b) It will be seen that the portion (b) represents, for the same rates of flow, higher differential head conditions than the portion (a). The reason for this is that in order to conduct experiments at high values of the head, ΔH, the constant head device, ("B" in Figure 15) was raised, necessitating the insertion of an extra length of feed tube. The added resistance to flow caused by the introduction of this tube is responsible for the displacement of the upper portions of the curves. In the subsequent correction of the experimental data for the resistance of the apparatus, the appropriate portion of the curve of Table XVIII was used, depending on whether or not the extra length of feed tube was in use during the experiment. In the tables which follow, those values of ΔH which were referred to the portion (a) of the curve of Table XVIII, for correction have been indicated by means of an asterisk *.

Correcting the curves for the sand bed according to the resistance to flow of the apparatus without the sand bed, gives the curves shown in Figure 17.

Figure 16

GRAPH SHOWING RELATIONSHIP BETWEEN PRESSURE DROP AND RATE OF FLOW OF FLUID FROM TABLES XVIII TO XXI.

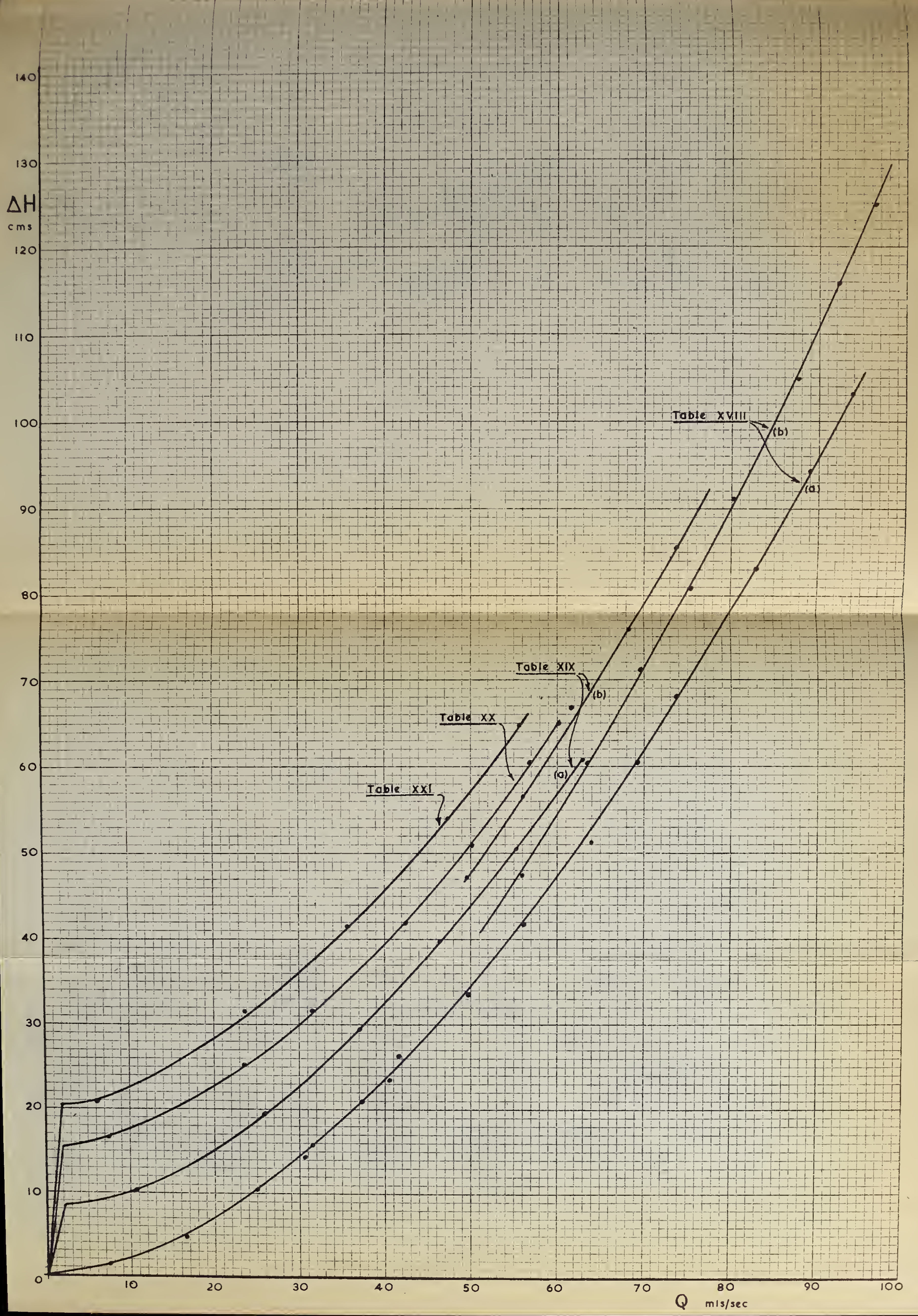
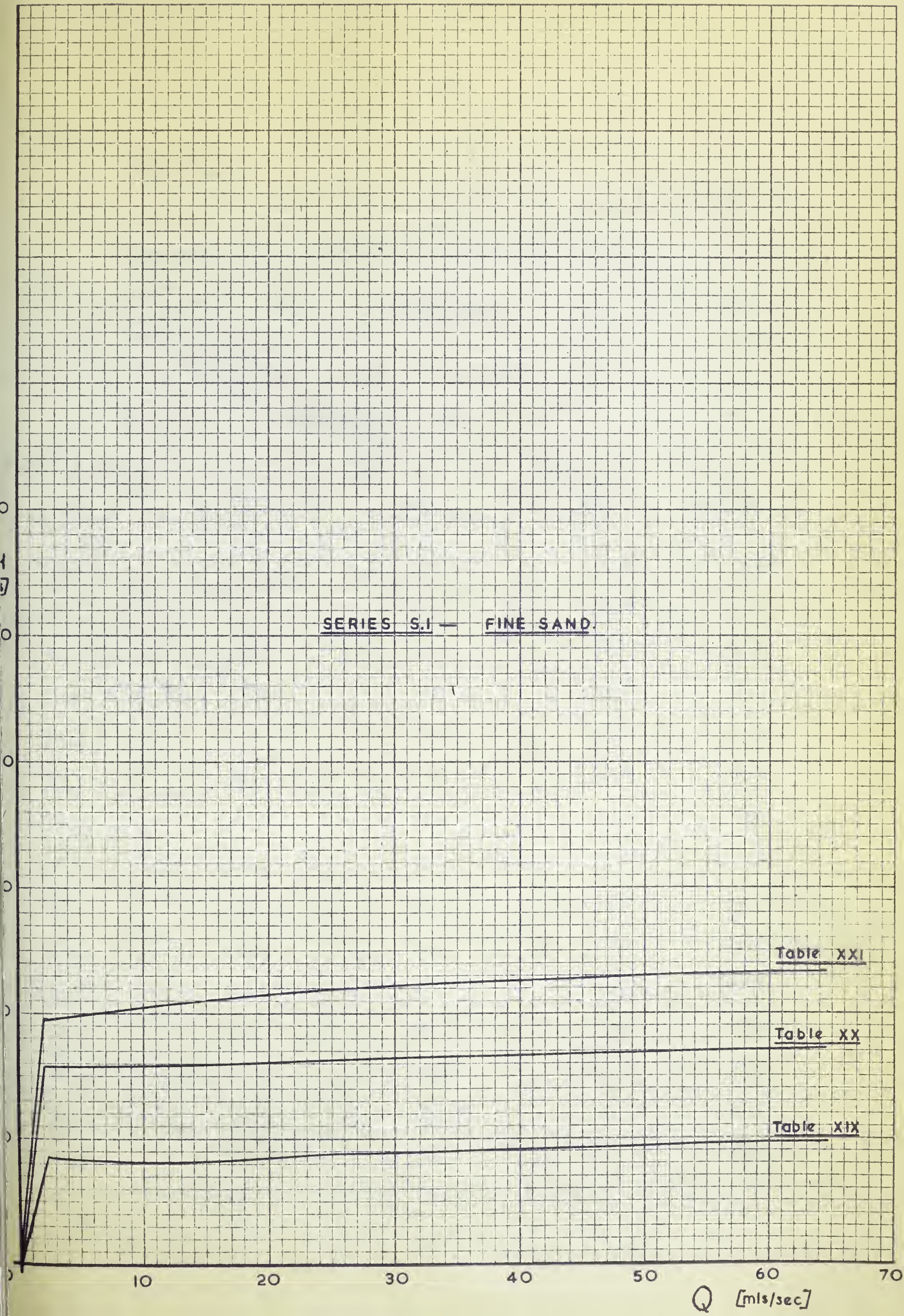

ΔH
cms
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
10
20
30
40
50
60
70
80
90
100
Q mls/sec
Table XVIII
(b)
(a)
Table XIX
(b)
(a)
Table XX
Table XXI

Figure 17

GRAPH SHOWING RELATIONSHIP BETWEEN PRESSURE DROP AND RATE OF FLUID FLOW FOR FINE SAND BEDS.



SERIES S.1 — FINE SAND.

Series S. 2.

This series was carried out with medium sized sand. The following tables are similar to those in Series 1.

Table XXII

Depth of bed - 19.7 cms.

Temperature of water - 23 °C

Depth of bed L cms.	Differential Head Δ H cms.	Volume Measured V mls	Time of flow of V mls. secs.	Rate of flow Q mls/sec.	
19.7	--	--	--	--	
19.7	1.9	100	130.0	0.77	
19.7	4.3	100	55.5	1.8	
19.7	6.6	250	91.0	2.8	
19.7	9.0	250	67.0	3.7	
19.7	11.4	250	53.4	4.7	
19.7	13.7	250	45.0	5.6	
19.7	15.3	250	40.0	6.3	
19.7	17.4	250	35.4	7.1	
20.5	20.2	500	34.5	14.5	Averaged head and depth readings due to considerable oscillation (1 cm range)
21.0	22.0	500	27.0	18.5	
21.0	23.5	500	25.5	19.6	
22.5	27.5	1000	40.0	25.0	
24.5	32.2	1000	33.0	30.3	
26.3	36.9	1000	28	35.7	
27.5	40.9	1000	25	40.0	

Table XXIII

Depth of Bed - 29.9 cms.
Temperature of water - 23 °C

Depth of bed L cms.	Differential Head ΔH cms.	Volume Measured V mls	Time of flow of V mls. secs.	Rate of flow Q mls/sec.
29.9	4.6	250	191.8	1.3
29.9	9.4	250	101.2	2.5
29.9	16.4	250	58.0	4.3
29.9	19.0	500	100.2	5.0
29.9	25.4	500	74.0	6.8
30.6	29.0	540	58.0	8.6
31.0	29.0	1000	106.8	9.4
31.5	29.0	1000	92.5	10.8
31.8	29.6	1000	74.0	13.6
32.6	30.5	1000	63.6	15.8
33.2	32.0	1000	55.0	18.2
33.2	33.0	1000	49.8	20.1
34.0	33.5	6000	298.	20.1
34.0	34.2	2000	93.3	21.4
34.2	34.8	2000	90.0	22.2
34.8	36.2	2000	83.8	23.9
35.3	37.0	2000	80.0	25.0
36.0	38.3	2000	74.6	26.8
36.8	39.7	2000	71.2	28.1
37.2	40.7	2000	67.4	29.7
38.1	42.2	2000	63.3	31.6
39.0	42.8	6000	190.0	31.6

Averaged Reading
of head and depth
(1 cm range)

Depth of bed L cms.	Differential Head ΔH cms.	Volume Measured V mls	Time of flow of V mls. secs.	Rate of flow Q mls/sec.
39.3	44.4	2000	58.8	34.0
41.3	47.0	2000	56.6	36.7
42.0	48.4	2000	52.9	37.8
42.5	48.9	6000	158	38.0
46.0	56.0	6000	132	45.5
52.8	67.8	6000	109.4	54.9
58.0	78.2	6000	96.0	62.5
61.8	85.8	6000	68.2	68.1
67.5	95.7	6000	81.0	71.4
73.7	106.7	6000	93.8	81.4
85.2	107.2	8000	91.0	87.9

TABLE XXIV

Depth of bed - 40.9 cms.

Temperature of water - 19° C

Depth of bed L cms.	Differential Head ΔH cms.	Volume Measured V mls.	Time of flow of V mls. secs.	Rate of flow Q mls./sec.
40.9	-	-	-	-
40.9	7.2	250	189	1.32
40.9	12.3	250	107.8	2.32
40.9	16.6	250	79.2	3.16
40.9	19.6	500	134.4	3.72
41.0	25.6	500	101.2	4.94
41.1	28.7	500	89.5	5.59
41.2	31.3	500	80.0	6.25
41.3	36.3	4000	542.6	7.38
41.2	39.6	6000	762	7.88
42.7	39.0	6000	612	9.81
45.2	41.3	6000	437.6	15.9
49.7	46.8	6000	247.0	24.3
54.0	51.9	6000	198.0	30.3
58.9	57.6	6000	163.6	36.7
62.0	62.8	7000	168.2	41.6
66.6	68.8	6000	128.0	46.9
70.5	74.6	6000	117.0	51.3
74.5	79.5	6000	108.2	55.5
77.8	85.3	6000	101	59.4
82.2	90.3	8000	126.5	63.3
86.5	96.8	8000	118.8	67.4
90.8	102.0	8000	113.0	70.8

TABLE XXV

Depth of Bed - 50.4 cms.

Temperature of Water - 18 ° C

Depth of bed L cms.	Differential Head Δ H cms.	Volume Measured V mls.	Time of flow of V mls. secs.	Rate of flow Q mls./sec.
50.4	-	-	-	-
50.4	27.0	250	58.0	4.31
50.6	34.6	500	89.0	5.62
50.7	38.4	500	77.6	6.45
50.8	42.1	500	70.0	7.1
51.0	46.0	500	63.8	7.84
52.3	48.5	500	51.0	9.8
53.2	49.0	500	44.2	11.31
55.4	49.5	500	34.8	14.36
58.8	52.3	8000	412.2	19.4
64.8	58.2	6000	222.4	27.0
69.5	63.3	6000	182.4	32.9
75.7	69.3	6500	227.4	38.8
80.7	74.4	6000	138.4	43.4
85.3	79.9	6000	125.4	47.9
90.7	85.8	8500	160.9	57.8
96.0	92.4	6500	112.2	58.0
101.0	98.1	6000	97.6	61.5
106.5	104.4	6000	90.9	66.0

TABLE XXVI

Depth of Bed - 61.4 cms.

Temperature of water - 21 °C.

Depth of bed L cms.	Differential Head Δ H cms.	Volume Measured V mls.	Time of flow of V mls. secs.	Rate of flow Q mls./sec.
61.4	-	-	-	-
61.4	7.8	250	227.4	1.1
61.4	18.9	250	95.9	2.6
61.4	27.9	250	67.0	3.7
61.4	33.1	250	58.6	4.3
61.4	38.9	500	99.6	5.0
61.4	44.0	500	88.2	5.7
61.4	46.20	500	84.0	6.0
61.5	52.1	500	76.2	6.6
61.7	55.5	500	70.0	7.1
63.2	58.9	500	54.0	9.3
70.5	61.5	5500	310.8	17.7
79.2	68.5	5500	204.6	26.9
85.3	73.3	5500	168.4	32.7
88.3	77.1	8500	151.6	36.3
94.2	82.8	5500	132.2	41.6
100.5	88.7	5500	117.4	46.9
106.5	94.3	7000	135.8	51.5

The results obtained with this grade of sand, after correcting as previously, are shown in Figure 18.

[illegible]

[illegible]

[illegible]

[illegible]

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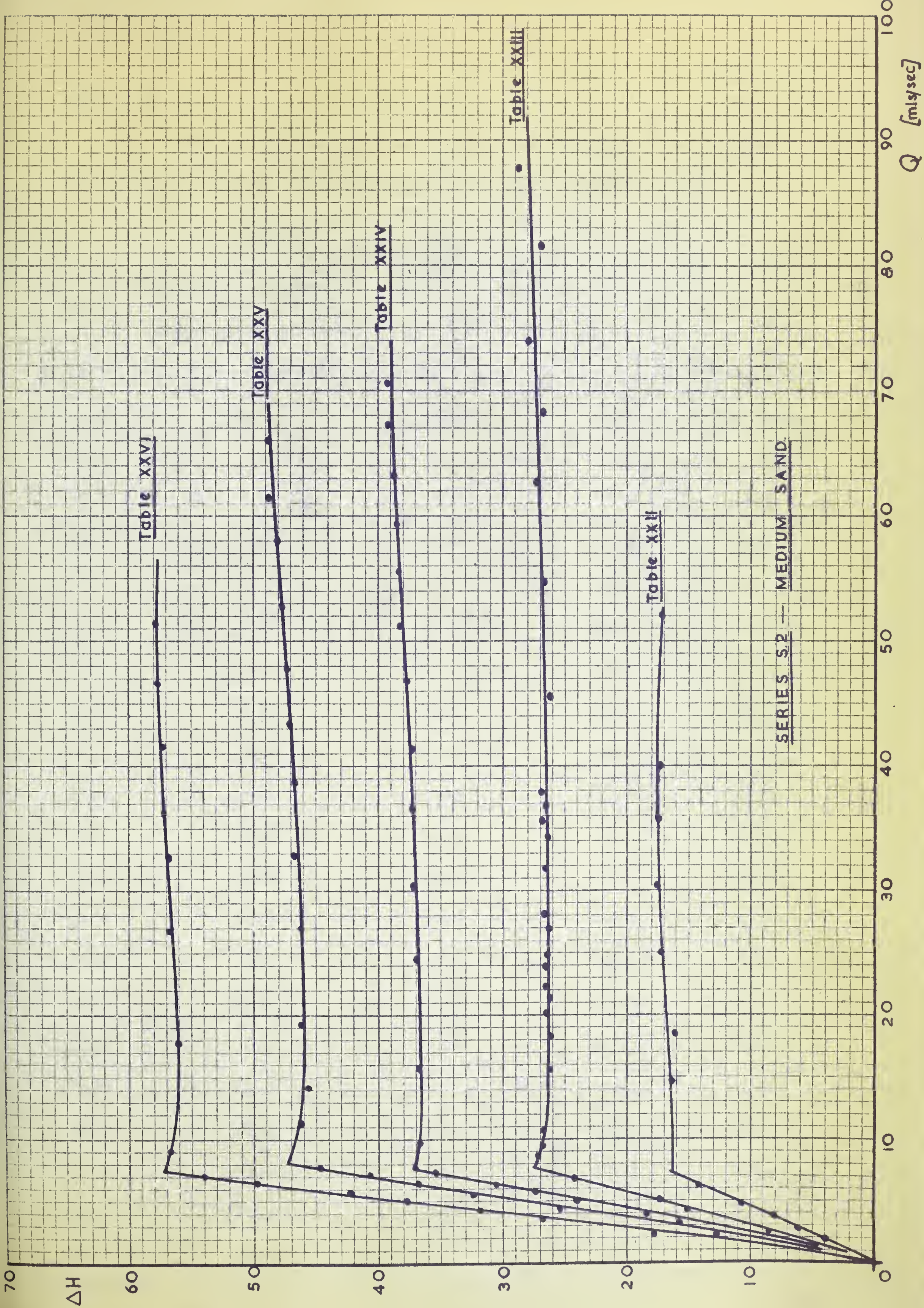
(Figure 18)

GRAPH SHOWING RELATIONSHIP BETWEEN PRESSURE DROP AND RATE OF FLUID FLOW FOR MEDIUM SAND BEDS.


SERIES S.2 — MEDIUM SAND.

Series S. 3.

This series was carried out with coarse sand. The results are given in Tables XXVII to XXXIII as in the preceding series.

TABLE XXVII

Depth of Sand Bed - 20.4 cms.

Temperature of water - 21 ° C.

Depth of Bed L cms.	Differential Head ΔH cms.	Volume Measured V mls.	Time of flow of V mls. secs.	Rate of flow Q mls./sec.
20.4	-	-	-	-
20.4	9.3	500	67.4	7.4
20.4	16.1	500	41.6	12.0
20.4	20.3	500	33.8	15.1
20.9	23.5	5500	289.2	19.0
21.3	28.3	5500	191.2	26.0
21.9	32.9	5500	216.2	31.2
22.9	39.1	5500	146.0	37.7
23.8	45.2	5500	126.4	43.5
24.5	49.4	6000	128.0	46.9
25.3	55.3	5500	106.2	51.8
26.5	61.0	6000	106.8	56.2
27.3	66.4	7000	116.6	60
27.8	72.5	7000	109.0	64.2
28.8	78.1	7000	102.4	68.3
29.9	84.0	7000	98.2	71.3
30.8	90.5	7000	92.4	75.7
31.7	95.5	7000	87.3	80.2
32.5	101.1	7000	84.0	83.3
33.1	105.9	7000	81.2	86.1

TABLE XXVIII

Depth of Bed - 30.5 cms.

Temperature of water - 19.0 ° C.

Depth of Bed L cms.	Differential Head ΔH cms.	Volume Measured V mls.	Time of flow of V mls. secs.	Rate of flow Q mls./sec.
30.5	-	-	-	-
30.5	10.4	500	89.0	5.6
30.5	16.3	500	58.2	8.6
30.5	22.6	500	43.0	11.6
30.5	26.9	5500	397.8	13.8
30.5	31.0	5500	355.2	15.5
30.9	32.3	5500	316.4	17.4
32.3	36.0	5500	236.0	23.3
33.4	40.7	5500	190.0	29.0
35.2	46.8	7000	195.6	35.8
36.2	51.9	6500	159.4	40.8
37.4	56.6	6500	144.2	45.0
38.5	61.3	7000	142.6	49.1
40.3	68.3	7000	127.8	54.7
41.4	73.7	7000	120.0	58.4
42.8	78.8	7000	112.8	62.1
44.3	85.1	7500	122.5	66.7
46.0	90.5	7000	100.4	69.7
47.0	95.4	6000	888.8	73.2

TABLE XXIX

Depth of Bed - 41.6 cms.

Temperature of water - 20 ° C.

Depth of Bed L cms.	Differential Head Δ H cms.	Volume Measured V mls.	Time of flow of V mls. secs.	Rate of flow Q mls./sec.
41.6	-	-	-	-
41.6	10.8	500	111.2	4.5
41.6	16.1	500	74.0	6.8
41.6	21.1	500	57.4	8.7
41.6	26.4	5500	502.6	10.9
41.6	30.9	5500	440.0	12.5
41.6	37.6	5500	389.0	14.1
41.6	42.8	5500	314.0	17.5
43.0	44.8	5500	261.6	21.0
44.4	47.8	5500	218.6	25.2
46.4	53.7	5500	173.6	31.7
48.3	58.0	5000	149.0	36.9
50.3	63.8	7000	165.0	42.4
52.5	69.7	5500	115.6	47.6
54.3	75.3	5500	105.2	52.3
56.5	82.1	5500	95.4	57.7
59.0	89.6	5500	87.4	62.9
61.3	95.7	5500	82.2	66.9
63.0	102.6	6000	84.0	74.5

TABLE XXX

Depth of Bed - 50.7 cms.

Temperature of water - 20 ° C.

Depth of Bed L cms.	Differential Head ΔH cms.	Volume Measured V mls.	Time of flow of V mls. secs.	Rate of flow Q mls./sec.
50.7	-	-	-	-
50.7	15.7	500	93.6	5.3
50.7	22.2	500	96.8	7.5
50.7	26.8	500	55.4	9.0
50.7	35.0	5500	459.0	12.0
50.7	41.3	5500	410.0	13.4
50.9	47.7	5500	372.0	14.8
50.9	51.7	5500	377.0	17.4
53.3	54.9	5500	245.2	22.4
56.7	61.1	6500	212.4	30.6
60.0	68.5	5500	143.2	38.4
63.1	75.4	5500	121.8	45.2
67.0	83.0	5500	108.0	50.9
69.8	90.1	5500	97.8	56.3
73.8	99.3	5500	86.8	63.4
76.2	107.0	5500	80.3	68.5

TABLE XXXI

Depth of Bed - 60.2 cms.

Temperature of water - 22 ° C.

Depth of Bed L cms.	Differential Head ΔH cms.	Volume Measured V mls.	Time of flow of V mls. secs.	Rate of flow Q mls./sec.
60.2	-	-	-	-
60.2	11.7	500	138.4	3.6
60.2	15.7	500	104.4	4.8
60.2	26.1	500	62.8	8.0
60.2	36.1	500	44.5	11.2
60.2	41.4	5500	449.4	12.2
60.2	52.4	5500	372.0	14.8
60.4	60.3	5500	320.0	17.2
62.4	62.3	5500	264.6	20.8
65.5	68.3	6000	217.2	27.6
67.0	69.5	5500	183.4	30.0
70.3	74.8	5500	153.8	35.8
73.3	80.3	5500	133.8	41.1
74.2	85.4	5500	119.0	46.2
77.2	91.1	5500	107.6	51.1
79.7	96.6	6000	109.2	55.0
82.0	101.2	5500	94.4	58.3
84.5	106.6	5500	88.4	62.3

TABIE XXXII

Depth of Bed - 70.6 cms.

Temperature of water - 22 °C.

Depth of Bed L cms.	Differential Head ΔH cms.	Volume Measured V mls.	Time of flow of V mls. secs.	Rate of flow Q mls./sec.
70.6	-	-	-	-
70.6	12.6	500	145.2	3.4
70.6	24.7	500	79.0	6.3
70.6	30.1	500	66.2	7.6
70.6	37.8	500	53.2	9.4
70.6	45.2	500	45.4	11.0
70.6	51.2	5500	441.6	12.6
70.6	59.6	5500	385.0	14.3
70.6	67.5	5500	349.2	15.8
75.0	74.2	5500	234.0	23.5
78.4	78.7	6000	208.4	28.8
83.0	85.2	5500	152.8	36.0
86.9	91.5	5500	131.2	42.0
91.3	98.4	6000	124.4	48.3
95.1	105.7	9000	168.2	53.5

TABLE XXXIII

Depth of Bed - 79.8 cms.

Temperature of water - 22 ° C.

Depth of Bed L cms.	Differential Head ΔH cms.	Volume Measured V mls.	Time of flow of V mls. secs.	Rate of flow Q mls./sec.
79.8	-	-	-	-
79.8	23.1	500	65	4.5
79.9	34.3	500	79.4	6.3
79.9	35.2	500	73.9	6.8
79.9	41.9	500	61.6	8.1
79.9	51.1	500	54.6	9.2
79.9	60.8	500	46.4	10.8
80.1	70.1	500	40.8	12.3
81.4	78.8	5500	402.0	13.7
85.6	83.3	5500	258.2	21.3
90.0	87.7	5500	203.2	27.0
96.3	95.3	5500	155.0	35.5
101.2	101.4	6500	156.2	41.7
106.3	108.4	5500	116.0	47.4

The results obtained with this grade of sand, after correction as previously, are shown in Figure 19.

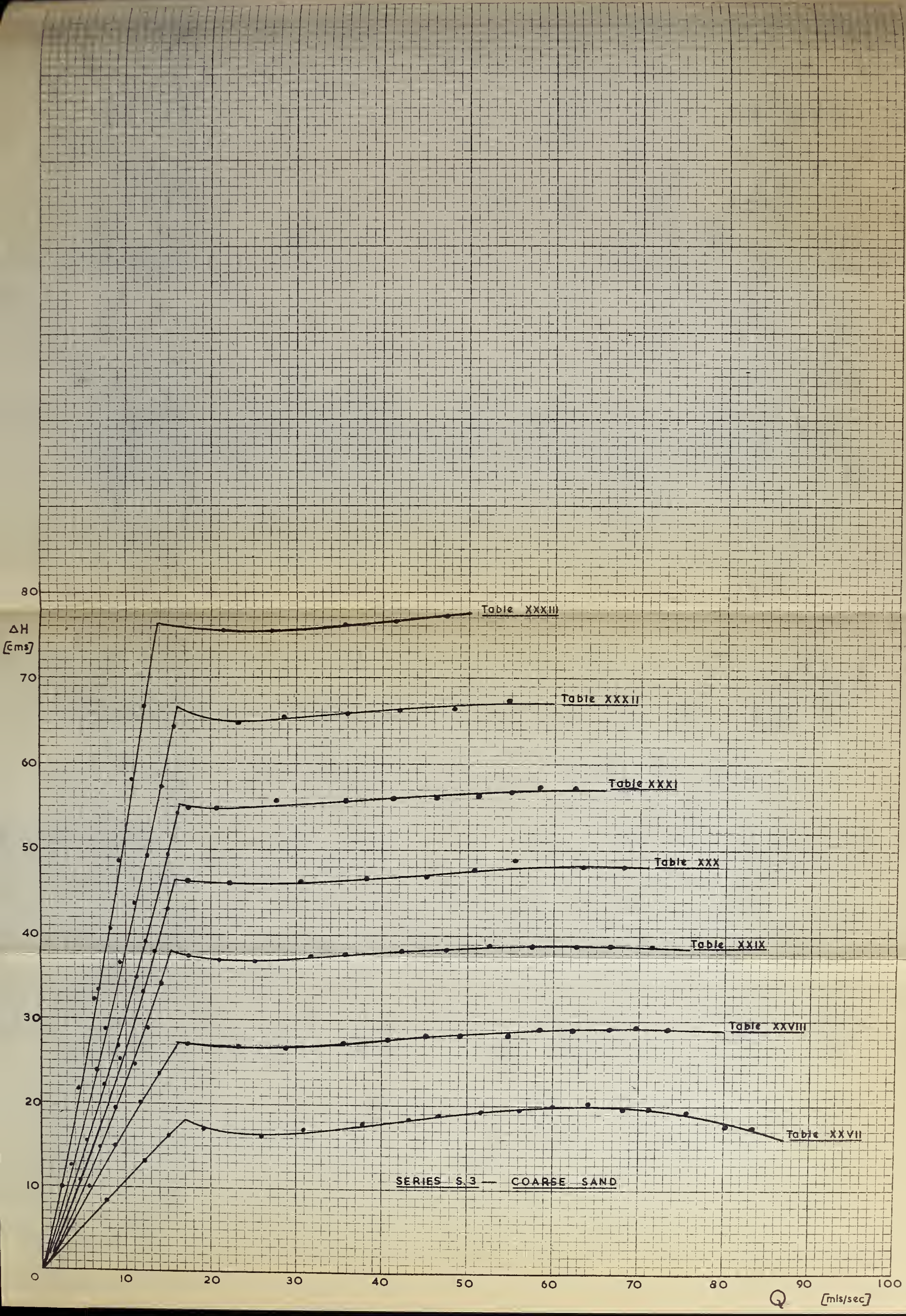
Considering Figures 17, 18 and 19

1. All the curves consist of two portions.

(a) A portion where the resistance varies linearly with the

(Figure 19)

GRAPH SHOWING RELATIONSHIP BETWEEN PRESSURE DROP AND RATE OF FLUID FLOW FOR COARSE SAND BEDS.


SERIES S.3 — COARSE SAND
Table XXXIII
Table XXXII
Table XXXI
Table XXX
Table XXIX
Table XXVIII
Table XXVII
ΔH
[cms]
80
70
60
50
40
30
20
10
0
10
20
30
40
50
60
70
80
90
100
Q
[mls/sec]

rate of flow. Over this portion the bed has expanded but has not reached the teetering condition. The relationship of the slopes of these portions of the curves to the initial depths of the beds is shown in Table XXXIV and Figure 20.

TABLE XXXIV

Flow Resistance of Sand beds

Fine		Medium		Coarse	
Initial Depth	Slope Sec/cm^2	Initial Depth	Slope Sec/cm^2	Initial Depth	Slope Sec/cm^2
9.4	3.5	19.7	2.2	20.4	1.1
17.7	7.5	29.9	3.6	30.5	1.7
24.0	9.5	40.9	4.9	41.7	2.5
		50.4	5.9	50.7	2.9
		61.4	7.7	60.2	3.3
				70.6	4.1
				79.8	5.4

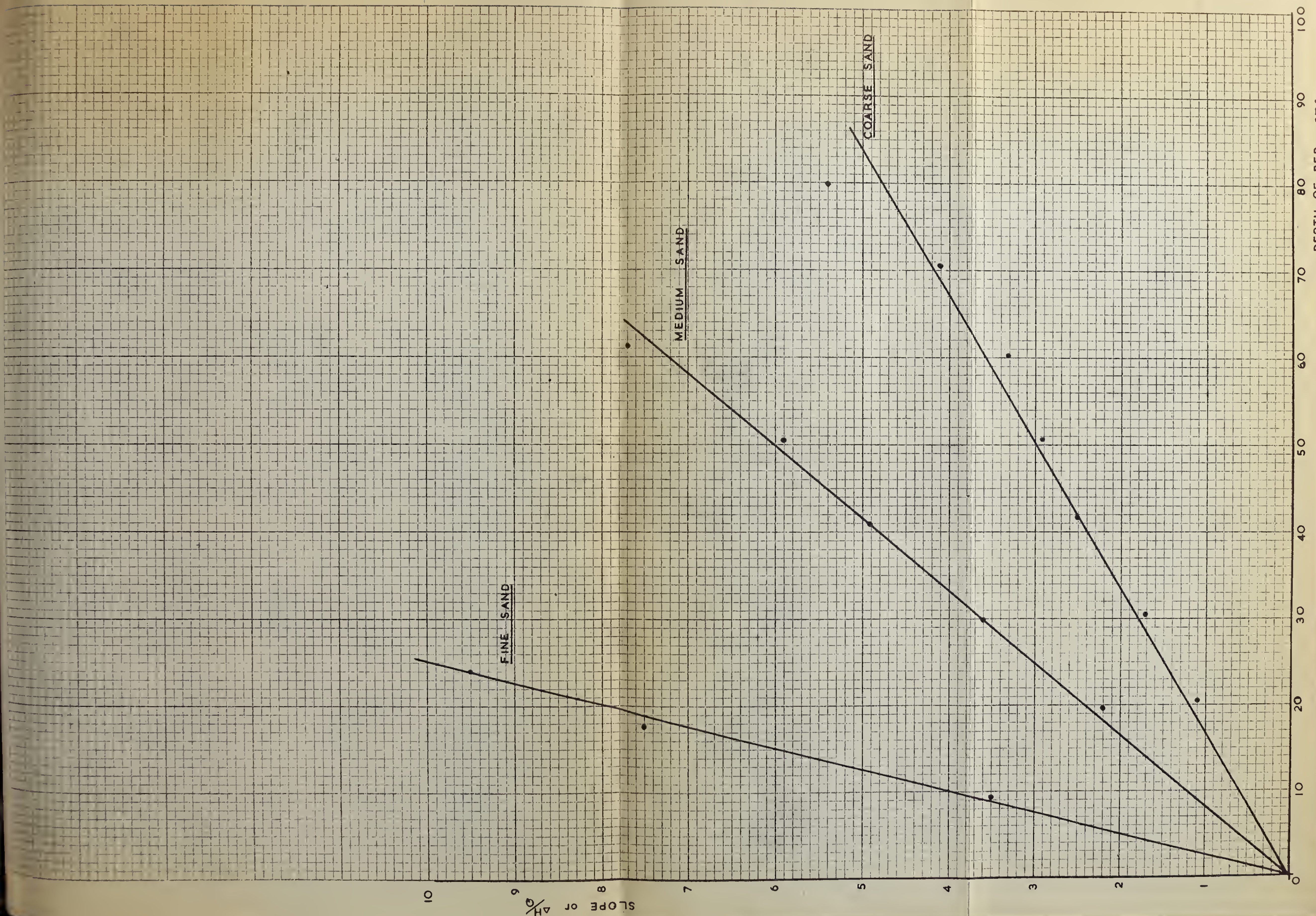
As will be obvious from Figure 20 the resistance of the bed for any particular size is in proportion to its initial depth of the bed.

(b) It is proposed to defer a discussion of the second part of these curves until results obtained with beds of materials of a different specific gravity have received consideration.

Moreover, with the results which will be detailed later, the subject can be better approached by methods of dimensional analysis.

(Figure 20)

THE RELATIONSHIP OF THE SLOPE OF THE PRESSURE DROP v. RATE OF FLUID FLOW CURVE TO THE DEPTH OF THE BED FOR CONSOLIDATED SAND BEDS.


COARSE SAND
MEDIUM SAND
FINE SAND
DEPTH OF BED. cms
0
10
20
30
40
50
60
70
80
90
100
SLOPE of ΔH/Q
1
2
3
4
5
6
7
8
9
10

2. A tendency will be observed for a slightly increased resistance at the junctions of the two portions of the curve before the slightly lower constant value is attained.

Figure 21 emphasizes this occurrence diagrammatically. The occurrence is much more marked in experiments to be described later.

(b) Experiments with Galena

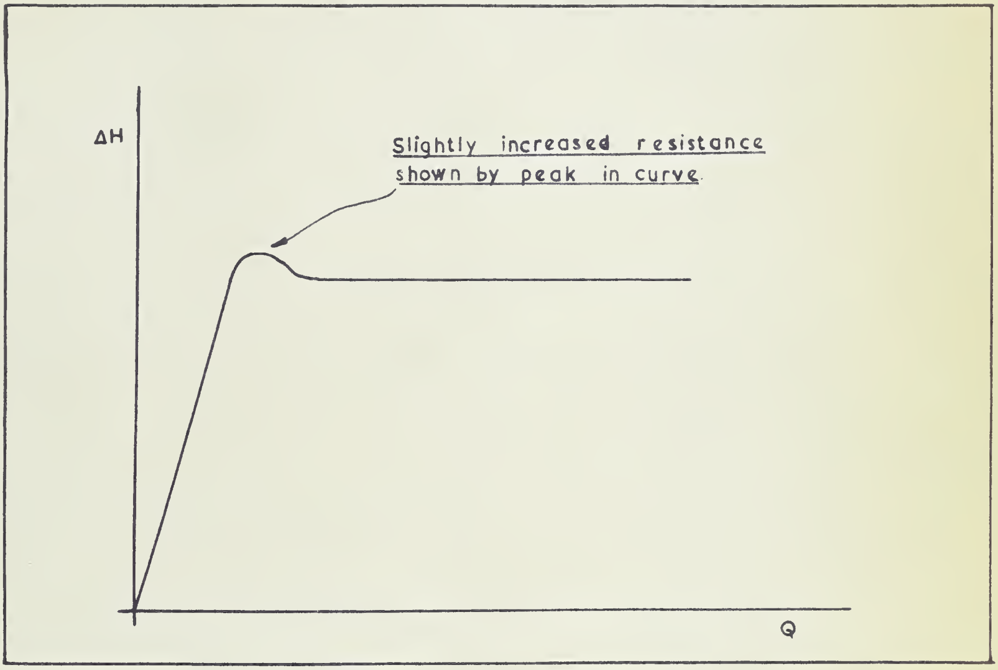
Galena was selected as a material of high specific gravity for use in a similar series of experiments to those described previously. The source of the sample of galena used was stated to be the Sullivan Mine of the Consolidated Mining and Smelting Co. in British Columbia. The sample was uniformly crystalline throughout.

The sample was reduced in size in a jaw crusher followed by crushing rolls, and sieved through Tyler screens of the same mesh as used for sizing the sand.

The specific gravity of the sample was determined using the conventional specific gravity bottle method. The specific gravity was 6.5 g/ml. Series of experients were then carried out with the fine, medium and coarse galena.

(Figure 21)

DIAGRAM SHOWING GENERALISED FORM OF PRESSURE DROP v. RATE OF FLUID FLOW CURVES.


ΔH
Slightly increased resistance shown by peak in curve.
Q

Series G.1

TABLE XXXV

Depth of Bed - 10.4 cms.

Temperature of Water - 18 °C.

Depth of Bed L cms.	Differential Head ΔH cms.	Volume Measured V mls.	Time of flow of V. mls. secs.	Rate of flow Q mls./sec.	
10.4	-	-	-	-	
10.4	9.2	500	105.8	4.7	
10.4	18.5	500	54.0	9.3	
10.4	24.2	500	42.6	11.8	
10.5	33.0	5500	203.8	27.0	
10.8	29.0	5500	248.0	22.2	x Unsteady conditions in bed. Average of head and depth of bed between x
11.0	36.7	5500	175.5	31.3	
11.0	43.2	5500	146.4	37.6	
11.3	49.3	5500	127.1	43.3	
11.3	56.7	5500	111.8	49.2	
12.5	64.7	5500	99.6	55.3	
12.5	69.8 *	5500	99.0	55.6	
13.5	75.7 *	6000	101.0	59.4	
13.5	72.2	5500	91.0	60.4	
13.0	80.6 *	6000	96.0	62.6	
14.0	87.0 *	6000	90.8	66.2	
14.2	80.2	5500	83.8	65.6	
15.3	97.2 *	5500	82.1	76.3	
14.5	88.9	5500	77.8	70.7	
16.0	101.3 *	7000	94.4	74.2	x
15.2	104.7	6000	78.8	76.2	

Depth of Bed L cms.	Differential Head ΔH cms.	Volume Measured V mls.	Time of flow of V mls. secs.	Rate of flow Q mls./sec.
16.0	111.3 *	7000	87.2	80.3
16.5	116.3 *	7000	86.2	81.2
17.5	124.2 *	7000	80.6	86.9
18.0	130.1 *	6000	67.8	88.5
19.0	135.8 *	5500	60.6	90.8

TABLE XXXVI

Depth of Bed - 21.8 cms.

Temperature of water - 16 ° C.

Depth of Bed L cms.	Differential Head Δ H cms.	Volume Measured V mls.	Time of flow of V mls. secs.	Rate of flow Q mls./sec.
21.8	-	-	-	-
21.8	14.2	500	149.0	3.4
21.8	21.9	500	98.6	5.1
21.8	31.2	500	66.0	7.6
21.8	36.3	500	56.7	8.8
21.8	42.9	500	47.1	10.6
22.5	51.0	5500	298.0	18.5
22.0	53.0	500	36.8	13.6
22.5	53.8	5500	245.0	22.5
23.2	63.0	5500	177.2	31.0
26.1	74.0	5500	137.0	40.2
28.4	82.3	5500	66.8	47.1
31.3	92.3	5500	100.2	55.0
30.0	96.2 *	5500	101.0	54.4
33.5	101.7	5500	89.6	61.4
33.0	106.7 *	5500	91.0	60.4
35.0	116.7 *	5500	82.6	66.6
38.0	127.4 *	7000	96.8	72.4
41.0	138.2 *	7000	89.8	78.0
43.0	148.0 *	7500	90	83.4

TABLE XXXVII

Depth of Bed - 26.2 cms.

Temperature of water - 16.7 ° C.

Depth of Bed L cms.	Differential Head ΔH cms.	Volume Measured V mls.	Time of flow of V mls. secs.	Rate of flow Q mls./sec.
26.2	-	-	-	-
26.2	13.1	500	204.8	2.4
26.2	23.2	500	118.6	4.2
26.3	38.3	500	68.2	7.3
26.4	49.6	500	51.4	9.7
26.6	59.4	500	41.8	12.0
26.3	60.5 *	500	46.6	10.7
26.7	63.2	500	39.0	12.8
26.8	64.9 *	500	38.4	13.0
26.3	65.0 *	500	43.2	11.6
27.8	65.0 *	605	28.4	31.3
27.2	67.5 *	500	37.8	13.2
26.9	68.1	500	35.4	14.1
28.0	69.5 *	5500	217.6	25.3
29.5	78.0 *	5500	171.6	32.0
32.5	87.5 *	5500	140.8	39.1
36.0	97.7 *	5500	117.6	46.8
39.9	108.8 *	5500	102.2	53.8
42.5	118.4 *	5500	91.6	60.1
45.5	128.2 *	6000	90.8	66.1
48.5	139.0 *	8000	110.8	72.2
51.5	147.3 *	7000	91.8	76.2

The results obtained with this grade of galena after correcting as in the case of sand, are shown in Figure 22.

Series G.2

TABLE XXXVIII

Depth of Bed - 19.9 cms.

Temperature of water - 21 °C.

Depth of Bed L cms.	Differential Head Δ H cms.	Volume Measured V mls.	Time of flow of V mls. secs.	Rate of flow Q mls./sec.
19.9	-	-	-	-
19.9	10.4	500	75.8	6.6
19.8	12.9	500	74.2	6.3
19.8	16.5	500	64.6	7.7
19.8	20.8	500	57.6	9.5
19.8	27.3	500	42.0	11.9
19.8	33.7	500	35.8	13.9
19.8	41.5	5500	351.0	15.7
20.9	49.9	5500	241.4	22.8
20.8	62.6	5500	183.4	30.0
21.7	67.7	5500	150.8	36.5
22.2	69.6	8000	191.0	41.9
22.8	76.5	8000	160.8	49.7
23.0	83.5	7000	122.8	57.0
23.5	92.5	7000	113.2	61.8
24.0	105.3	8000	117.9	67.9
23.8	91.3 *	8000	140.2	57.1
24.0	102.0 *	8000	128.0	62.5
24.5	114.8 *	8000	115.8	69.1x Unsteady conditions
26.0	126.0 *	8000	104.5	76.6x in bed. Averaged read-
26.7	138.5 *	9650	116.8	82.6x ings for head & depth.

(Figure 22)

GRAPH SHOWING RELATIONSHIP BETWEEN PRESSURE DROP AND RATE OF FLUID FLOW FOR FINE GALENA BEDS.

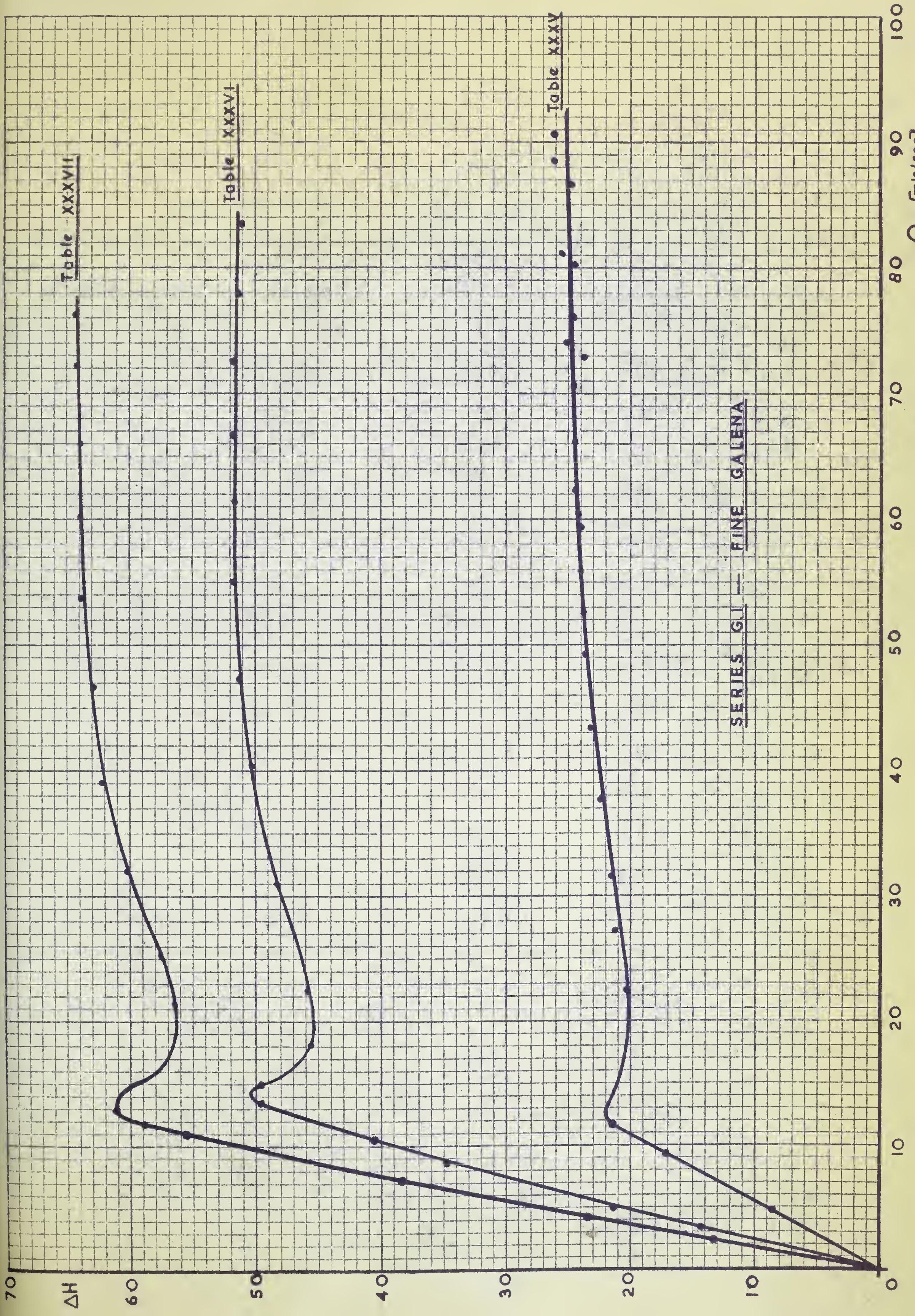

SERIES G.I — FINE GALENA
Table XXXVII
Table XXXVI
Table XXXV
ΔH
70
60
50
40
30
20
10
0
10
20
30
40
50
60
70
80
90
100
Q [mls/sec]

TABLE XXXIX

Depth of Bed - 30.7 cms.

Temperature of water - 19.5 ° C.

Depth of Bed L cms.	Differential Head Δ H cms.	Volume Measured V mls.	Time of flow of V mls. secs.	Rate of flow Q mls./sec.
30.7	-	-	-	-
30.7	19.0	500	64.4	7.8
30.7	38.0	500	33.8	14.8
30.8	51.7	500	24.8	20.2
31.3	47.7 *	5500	270.6	20.3
31.2	59.7 *	5500	230.0	23.9
31.3	70.2 *	6000	219.6	27.3
31.4	82.2 *	5500	178.6	30.8
31.5	89.2 *	5500	168.6	32.6
32.7	92.0 *	5500	146.0	37.7
34.2	102.8 *	5500	127.0	43.3
35.5	114.9 *	5500	100.2	54.9
37.0	126.3 *	5500	89.3	61.6
38.0	137.8 *	6500	94.8	68.6
39.0	149.1 *	7000	94.0	74.5

TABLE XL

Depth of Bed - 40.0 cms.

Temperature of water - 18 ° C.

Depth of Bed L cms.	Differential Head Δ H cms.	Volume Measured V mls.	Time of flow of V mls. secs.	Rate of flow Q mls./ sec.
40.0	-	-	-	-
40.0	15.8	500	97	5.2
40.0	28.5	500	55	9.1
40.0	56.1	500	29	17.3
40.4	48.4 *	5500	356.0	15.5
40.4	57.5 *	5500	303.5	18.1
40.6	69.8 *	5500	263.8	20.9
40.7	78.5 *	5500	245.0	22.5
40.5	86.5 *	5500	208.0	26.5
41.3	95.6 *	5500	189.8	29.0
41.8	101.7 *	5500	172.0	32.0
42.2	109.3 *	5500	158.2	34.8
42.2	116.7 *	5500	150.6	36.5
44.5	122.7 *	5500	124.0	44.4
46.0	130.5 *	6000	118.6	50.6
47.5	142.5 *	7000	120.0	58.3
49.5	152.5 *	6000	94.6	63.4

TABLE XLI

Depth of Bed - 46.8 cms.

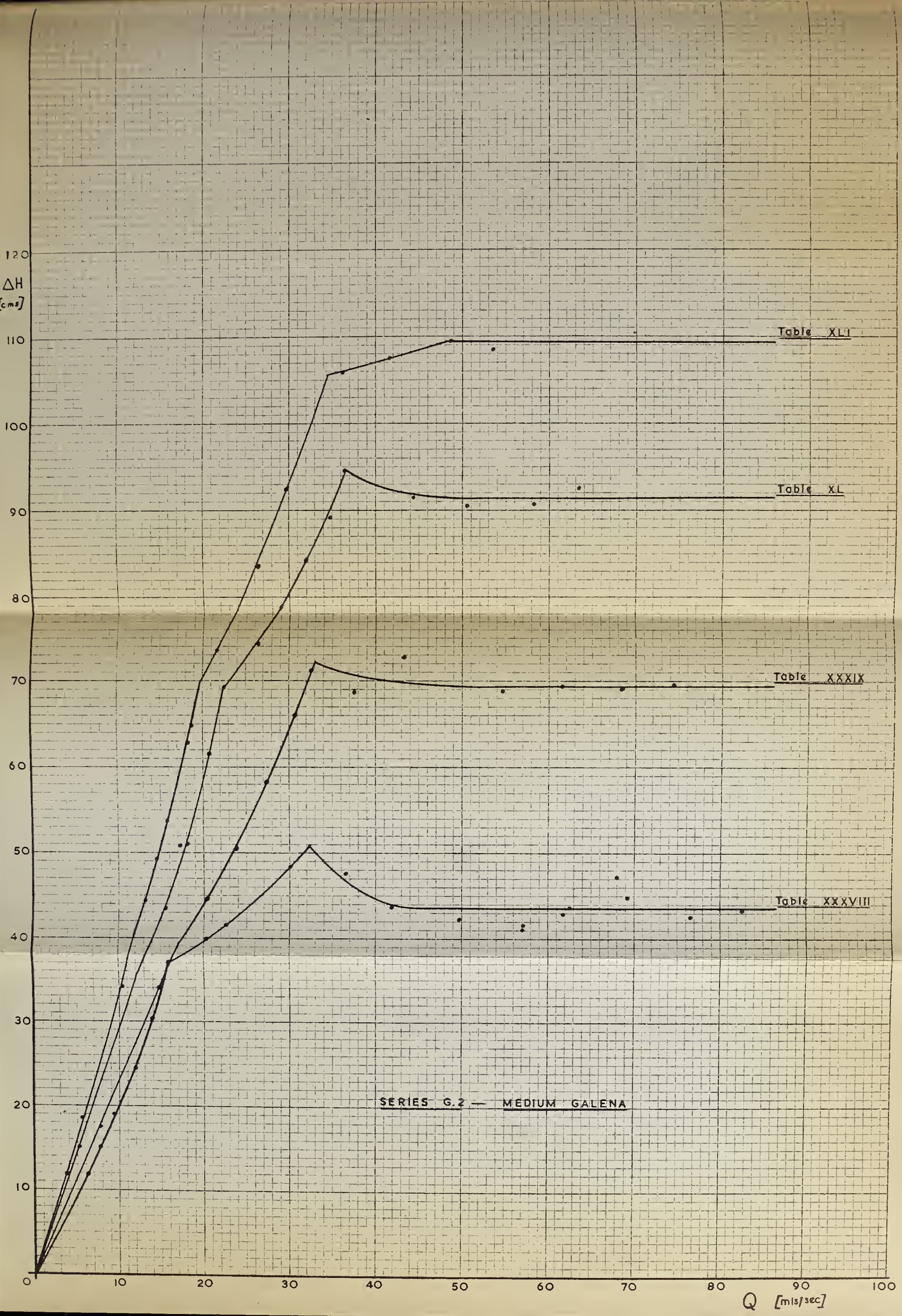
Temperature of water - 17 ° C.

Depth of Bed L cms.	Differential Head ΔH cms.	Volume Measured V mls.	Time of flow of V mls. secs.	Rate of flow Q mls./sec.
46.8	-	-	-	-
46.8	12.4	500	129.4	3.9
46.8	19.3	500	87.2	5.7
46.8	36.2	500	48.4	10.3
46.9	53.2	500	34.5	14.5
47.0	68.5	500	27.4	18.3
47.0	48.0 *	500	38.2	13.1
47.1	58.9 *	500	31.4	15.9
46.6	71.0 *	5500	292.2	18.8
46.9	82.1 *	5500	263.8	21.7
48.0	96.2 *	5500	207.0	26.6
48.3	107.8 *	5500	184.0	29.9
49.6	125.8 *	5500	151.9	36.2
50.0	135.5 *	5500	131.8	41.7
53.3	141.8 *	5500	113.0	48.7
55.2	152.2 *	5500	102.2	53.8

The results obtained with this grade of galena, after correction as previously, are shown in Figure 23.

(Figure 23)

GRAPH SHOWING RELATIONSHIP BETWEEN PRESSURE DROP AND RATE OF FLUID FLOW FOR MEDIUM GALENA BEDS.


SERIES G.2 — MEDIUM GALENA

Series G.3

TABLE XLII

Depth of Bed - 11.2 cms.

Temperature of water - 15 ° C.

Depth of Bed L cms.	Differential Head Δ H cms.	Volume Measured V mls.	Time of flow of V mls. secs.	Rate of flow Q mls./sec.
11.2	-	-	-	-
11.2	8.1	500	37.8	13.2
11.2	18.7	500	20.7	24.2
11.2	30.4	5500	164.8	33.7
11.4	52.5	5500	114.2	48.2
11.4	64.2	5500	102.1	53.9
11.4	74.1	5500	90.6	60.7
11.4	62.0 *	5500	118.0	46.6
11.4	69.5 *	7500	134.5	55.8
11.3	79.3 *	7000	116.4	60.1
11.4	85.6 *	7000	110.5	63.4
11.7	91.3 *	7500	110.4	69.5
12.0	103.0 *	7000	94.0	74.5

TABLE XLIII

Depth of Bed - 21.8 cms.

Temperature of water - 16.7 ° C.

Depth of Bed L cms.	Differential Head ΔH cms.	Volume Measured V mls.	Time of flow of V mls. secs.	Rate of flow Q mls./sec.
21.8	-	-	-	-
21.8	10.0	500	44.8	11.2
21.8	21.2	500	24.2	20.7
21.8	32.3	500	18.4	27.2
21.8	40.7	5500	169.0	32.6
21.8	52.7	5500	141.6	38.9
21.8	62.7	5500	125.6	43.8
22.0	75.3	5500	107.5	51.2
22.0	81.7	5500	99.4	55.3
22.3	91.1 *	5500	69.2	55.5
22.3	97.1	6000	98.6	60.9
22.3	103.1 *	5500	92.0	59.8
22.3	108.3	5500	84.4	65.2
22.3	114.8 *	5500	84.2	65.3
23.2	124.8 *	5500	75.0	73.3
23.7	136.1 *	5500	72.0	76.1
23.8	146.2 *	6000	72.0	83.3

TABLE XLIV

Depth of Bed - 27.0 cms.

Temperature of water - 17.8 ° C.

Depth of Bed L cms.	Differential Head △ H cms.	Volume Measured V mls.	Time of flow of V mls. secs.	Rate of flow Q mls./sec.
27.0	-	-	-	-
27.0	10.5	500	49.4	10.1
27.0	20.8	500	27.6	18.1
27.0	30.5	500	21.0	23.8
27.0	40.6	5500	186.8	29.5
27.1	46.7 *	5500	174.2	31.6
27.1	49.3	5500	163.4	33.7
27.1	61.7 *	5500	142.2	38.7
27.1	70.7 *	5500	129.6	42.4
27.2	84.9 *	6000	124.0	48.4
27.2	95.9 *	6000	114.2	52.5
27.3	109.1 *	5500	95.5	57.6
27.5	119.7 *	5500	89.4	61.5
27.8	131.2 *	7500	111.0	67.6
29.0	141.5 *	6500	87.2	74.5

TABLE XLV

Depth of Bed - 37.0 cms.

Temperature of water - 16.7 ° C.

Depth of Bed L cms.	Differential Head ΔH cms.	Volume Measured V mls.	Time of flow of V mls. secs.	Rate of flow Q mls./sec.
37.0	-	-	-	-
37.0	12.0	500	59.2	8.5
37.0	19.6	500	38.0	13.2
37.1	32.6	5500	267.0	20.6
37.1	43.0	5500	216.8	25.4
37.1	52.7	5500	185.0	29.7
37.1	65.2	5500	158.6	34.7
37.1	71.7	5500	147.8	37.2
37.1	87.0	5500	128.4	42.9
37.1	95.1	8500	186.2	45.6
37.1	105.3	6500	130.2	49.9
36.8	123.0 *	5500	99.8	55.1
37.4	123.3 *	5500	100	55.0
38.0	130.4 *	5500	92.6	59.4
38.0	138.2 *	5500	80.0	61.1
38.2	143.2 *	5500	87.8	62.6
38.2	146.5 *	5500	85.8	64.1
38.5	150.7 *	5500	83.6	65.8
38.7	154.5 *	5500	82.2	66.9
38.2	170.1 *	8500	115.2	73.8
39.5	181.8 *	8500	105.0	81.0

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[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

The results obtained with this grade of galena, after correction as previously, are shown in Figure 24.

(c) Experiments with Coal

A parallel series of experiments was carried out using a sample of bituminous coal selected as representative of reasonably clean material, but without passing the coal through a cleaning process before use. The sample was ground and screened to give the three screen sizes used with the galena and sand.

Throughout, considerable experimental difficulties arose owing to bubbles of air adhering to the coal particles, so that many of them were carried out of the apparatus with the water stream. The inclusion of air within the bed materially reduced the effective specific gravity of the bed.

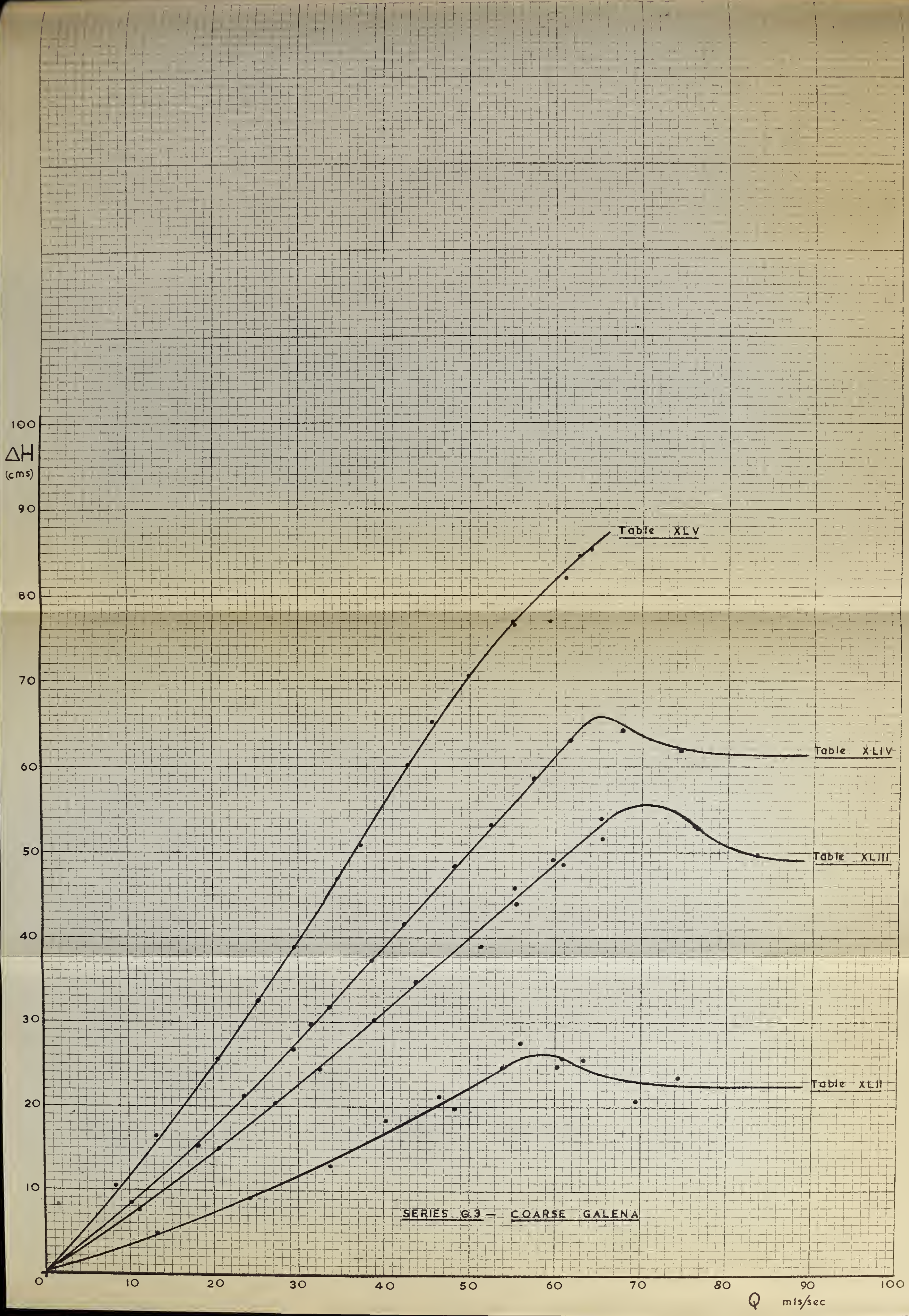
Particles floating to a varying degree immediately above the surface of the bed rendered the surface indefinite and it was difficult to determine where exact measurement should be made.

Before the coal was introduced into the tube it was necessary to thoroughly wet the coal surface using a small amount of a wetting agent, "Perminal W".

To remove the air at the commencement of an experiment the bed was stirred vigorously under water. As the experiment continued, however, air was apparently removed from the water by the coal causing a recurrence of the trouble. Accordingly, the experiment had repeatedly to be interrupted for removal of the accumulated air.

(Figure 24)

GRAPH SHOWING RELATIONSHIP BETWEEN PRESSURE DROP AND RATE OF FLUID FLOW FOR COARSE GALENA BEDS.


ΔH
(cms)
100
90
80
70
60
50
40
30
20
10
0
10
20
30
40
50
60
70
80
90
100
Q mls/sec
Table XLV
Table XLIV
Table XLIII
Table XLII
SERIES G.3 — COARSE GALENA

Series C.1

TABLE XLVI

Depth of Bed - 17.5 cms.

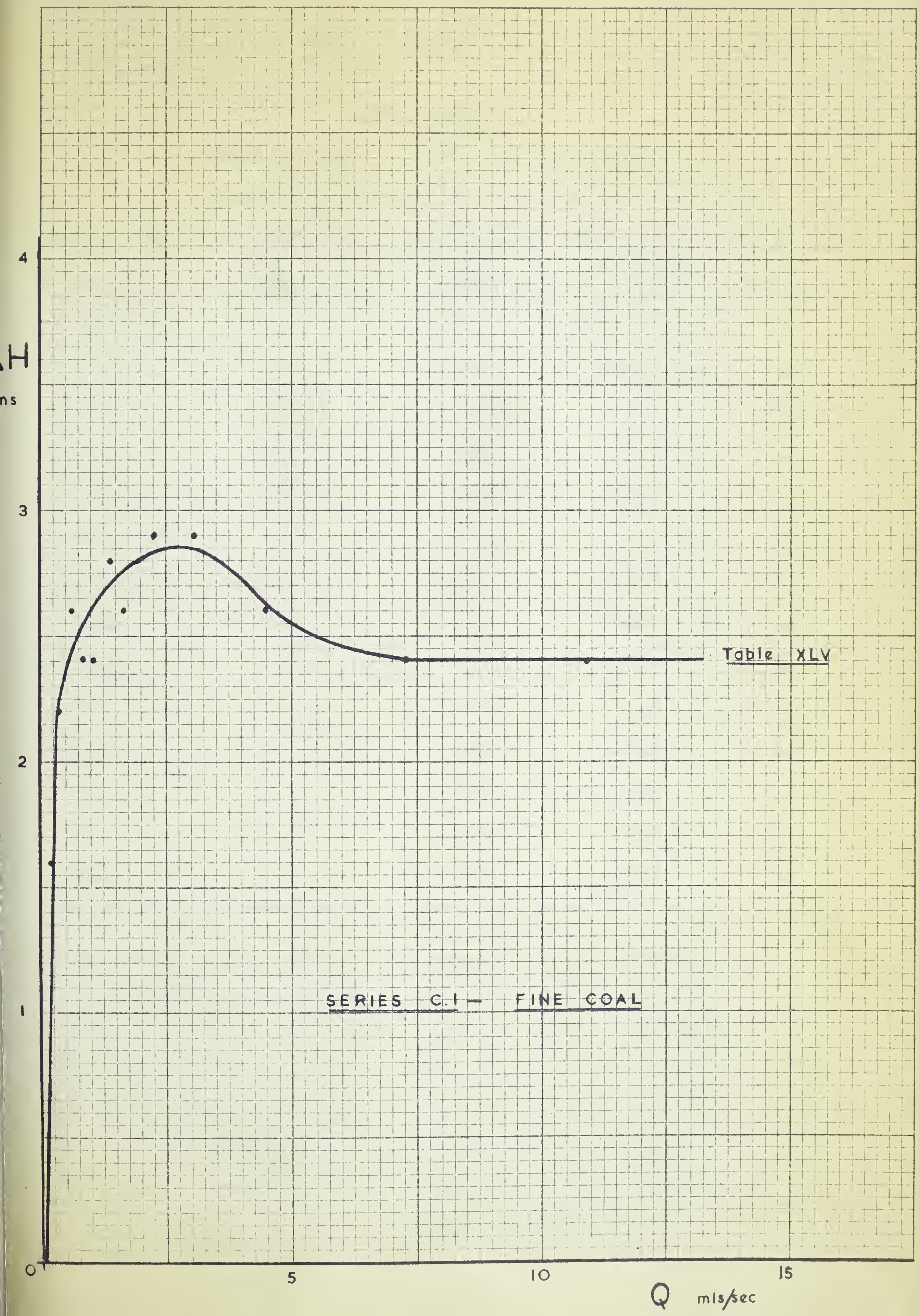
Temperature of water - 20 ° C.

Depth of Bed L cms.	Differential Head Δ H cms.	Volume Measured V mls.	Time of flow of V mls. secs.	Rate of flow Q mls./sec.
17.5	-	-	-	-
17.5	1.6	100	442.4	0.2
17.5	2.2	100	289.1	0.3
19.9	2.6	100	158.0	0.6
21.0	2.4	100	113.8	0.9
22.0	2.5	100	90.9	1.1
22.0	2.9	100	75.6	1.3
22.5	2.7	100	59.7	1.7
23.0	3.1	100	45.2	2.2
24.0	3.1	250	80.5	3.1
27.0	3.0	250	55.3	4.5
35.2	3.4	500	68.4	7.3
49.5	4.6	500	45.9	10.9

The results obtained with this grade of coal, after correcting as in the case of sand, are shown in Figure 25.

(Figure 25)

GRAPH SHOWING RELATIONSHIP BETWEEN PRESSURE DROP AND RATE OF FLUID FLOW FOR FINE COAL BEDS.


H
ns
4
3
2
1
0
5
10
15
Q mls/sec
Table XLV
SERIES C.1 — FINE COAL

Series C.2

TABLE XLVII

Depth of Bed - 17.5 cms.

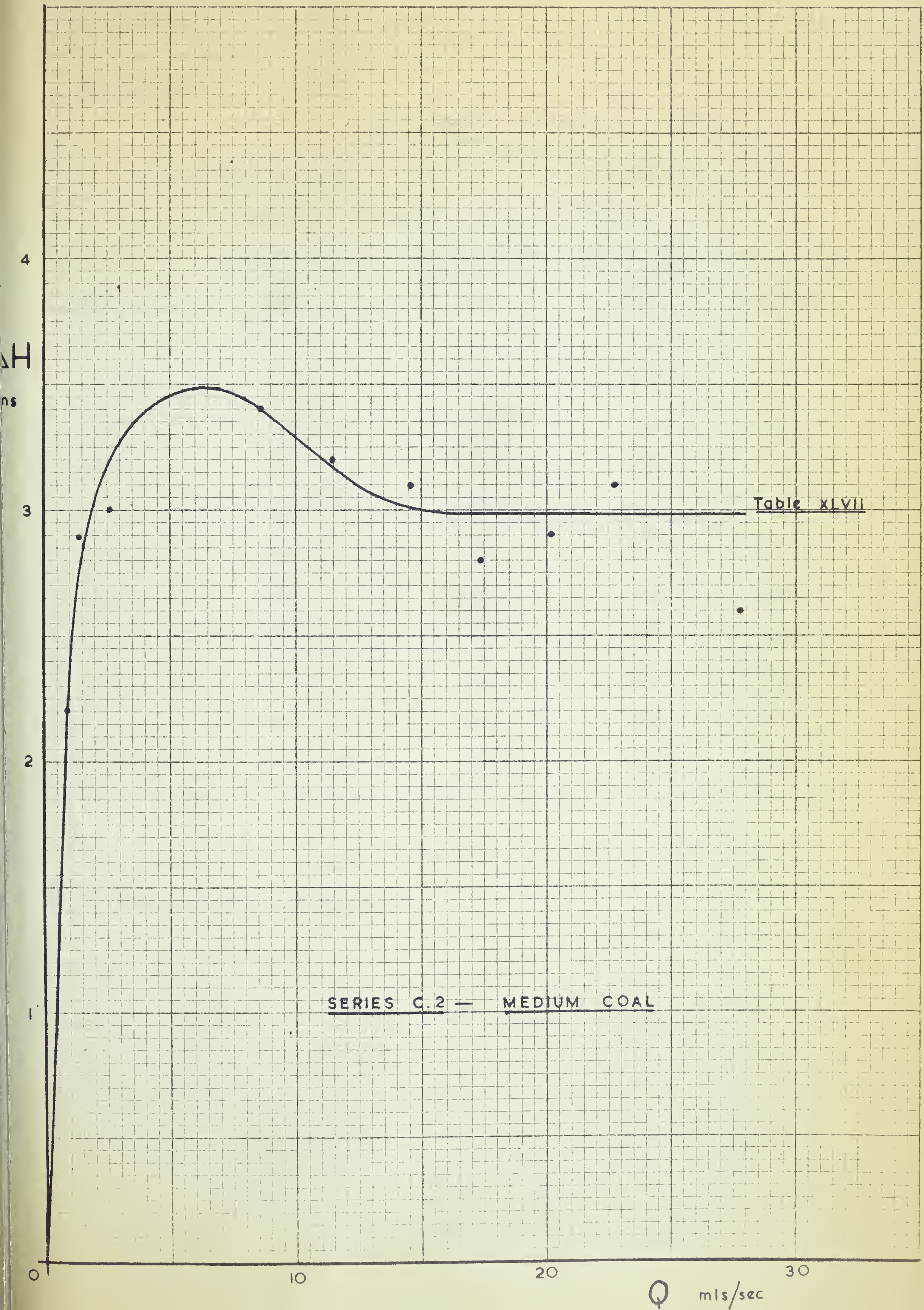
Temperature of water - 15 ° C.

Depth of Bed L cms.	Differential Head Δ H cms.	Volume Measured V mls.	Time of flow of V mls. secs.	Rate of flow Q mls./sec.
17.5	-	-	-	-
17.5	1.2	400	640.4	1.2
17.7	2.6	100	40.	2.5
17.9	3.2	400	124	3.2
19.4	3.5	500	122.8	4.1
19.0	2.8	500	133.2	3.8
22.8	5.4	500	49.5	10.1
23.6	6.6	500	40.1	12.5
26.5	9.1	500	27.8	18.0
30.5	12.9	500	21.4	23.4
37.6	19.2	5500	126.0	31.3
45.4	25.3	5500	144.2	38.1
56.7	33.2	5500	120.0	45.9
71.5	40.6	7000	135.2	51.8

The results obtained with this grade of coal, after correction as previously, are shown in Figure 26.

(Figure 26)

GRAPH SHOWING RELATIONSHIP BETWEEN PRESSURE DROP AND RATE OF FLUID FLOW FOR MEDIUM COAL BEDS.


SERIES C.2 — MEDIUM COAL

Series C.3

TABLE XLVIII

Depth of Bed - 17.2 cms.

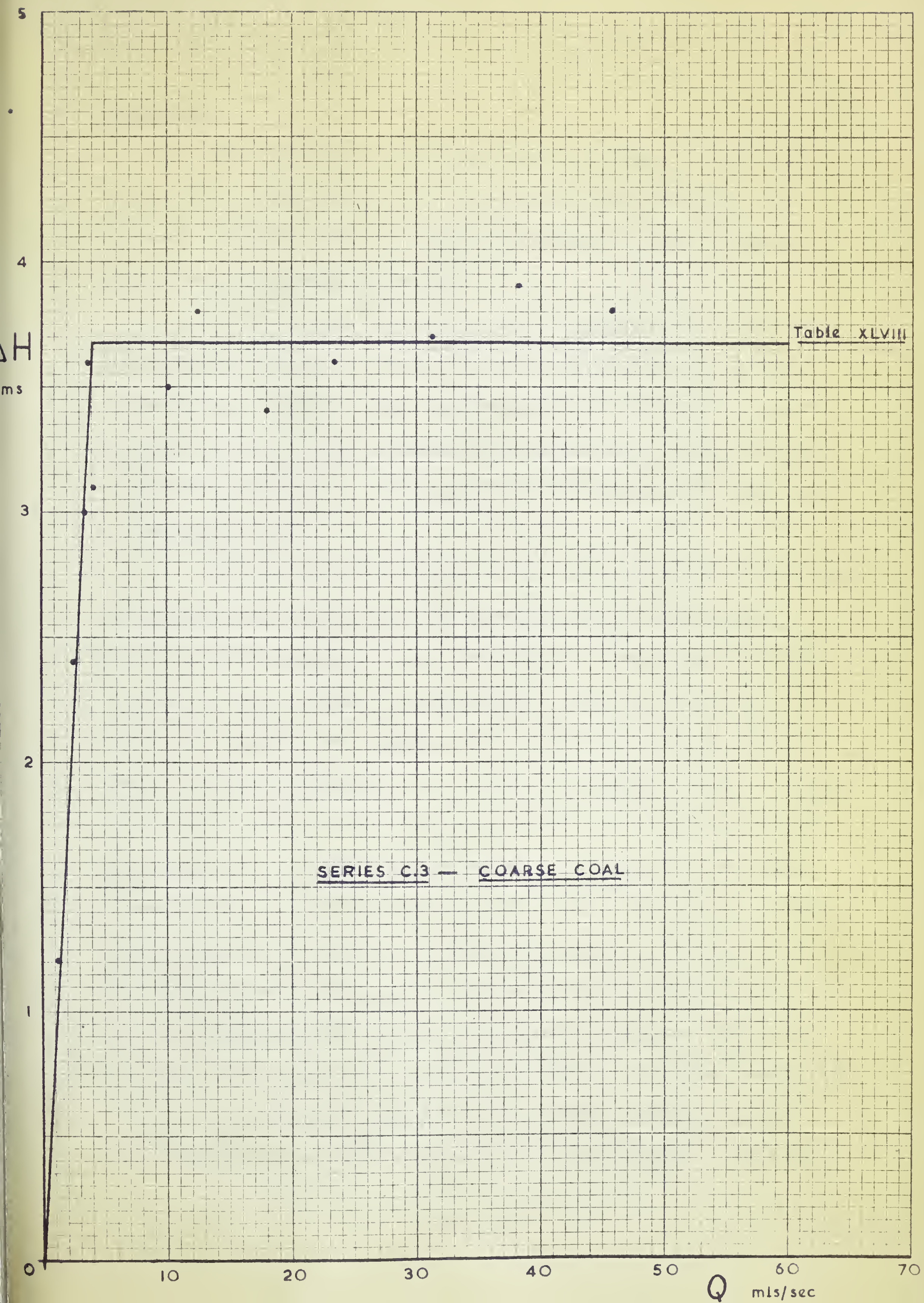
Temperature of water - 20 ° C.

Depth of Bed L cms.	Differential Head Δ H cms.	Volume Measured V mls.	Time of flow of V mls. secs.	Rate of flow Q mls./sec.
17.2	-	-	-	-
17.3	2.2	100	114.8	0.9
19.7	3.0	100	70.0	1.4
20.4	3.2	100	39.2	2.6
25.5	4.8	100	11.6	8.6
28.9	5.7	250	21.8	11.5
35.0	6.9	500	34.2	14.6
41.7	8.1	500	28.8	17.4
50.0	9.9	500	24.8	20.2
58.0	11.9	500	22.0	22.8
71.5	15.2	500	18.0	27.8

The results obtained with this grade of coal, after correction as previously, are shown in Figure 27.

(Figure 27)

GRAPH SHOWING RELATIONSHIP BETWEEN PRESSURE DROP AND RATE OF FLUID FLOW FOR COARSE COAL BEDS.



SERIES C.3 — COARSE COAL

Table XLVIII

CORRELATION

Many experimental and theoretical investigations have been carried out to establish the true relationship existing between the different variables which are factors governing the flow of fluids through beds of granular materials.

Rose(7) states that examination of published data shows great discrepancies between the results of the researches of the different investigators. There is little agreement between the results, and the equations which have been obtained by different workers are by no means of general application, in fact, most of them hold for but limited ranges of flow conditions.

This situation has arisen, in part at least, from the fact that in general, each research has been undertaken with a definite but strictly limited object in view. For example, an equation, by the use of which the rate of flow of fluid through a sand bed filter may be calculated, may have been derived, but no effort was made to obtain a general equation applicable to all fluids at any rate of flow. It seems reasonable to believe that a single law governs the flow of all fluids even though the exact mathematical expression stating this law may be so complicated that its formulation is practically impossible. It also seems reasonable to think that research may lead to the derivation of a single equation of flow, and that continued investigation may result in improved agreement between the calculated and experimental results as knowledge of the relationship between the different variables accumulates.

It is generally agreed that the methods of dimensional analysis provides one satisfactory approach to the problems of fluid flow,

but care has to be taken not to stretch the method to cover variables which are not independent of the conditions of geometrical similarity which the method imposes.

The dimensional variables are expressed in units of mass, length and time.

In the results to be given, the foot-pound-second system has been employed; although certain readings were taken in grams and centimetres, appropriate conversion factors have been used in the calculation.

Groups are formed from the dimensional variables by a definite process of selection so that their dimensions cancel each other out, leaving only a dimensionless ratio or simple number.

The number of groups which may be formed is equal to the difference between the number of variables and the number of dimensions.

Previous investigators have considered the following twelve variables in systems of this kind:-

1) diameter of container
2) depth of bed
3) mean size of particles
4) shape of the particles
5) the roughness of the surface of the particle
6) size distribution of particles in the bed
7) density of solid material
8) density of the fluid medium
9) viscosity of the fluid medium
10) linear velocity of flow of the fluid medium
11) pressure drop through the bed of solid
12) voidage of the bed

In the experiments to be described, only one container was used so that its diameter represents a constant and not a variable. The roughness of the surface has not been considered.

Limitations of time precluded the investigation of the influence of size distribution. Voidage is considered, as this variable is involved in the extension of the results of the dimensional analysis which follows.

The notation assigned to the variables studied is:-

depth of bed	L
mean size of particle	D_p
density of solid material	ρ_s
density of fluid medium	ρ_f
viscosity of liquid medium	μ
linear velocity of flow of fluid medium (in open tube)	U_m
pressure drop through the bed of solid	ΔP
voidage of the bed	ϵ

Instead of considering the true density, ρ_s, of the solid, it is more appropriate to consider what may be termed its effective density, $(\rho_s - \rho_f)$ when it is immersed in a fluid of density ρ_f.

Also, in order to facilitate the calculation of voidage values for the bed, a "reduced" depth of bed, L_o, will be used throughout in place of the initial depth, L_i. The depth of bed at any time after the initial conditions of no flow, will be designated by the term, L.

L_o and L_i are simply related since

$$L_o = L_i \times \frac{\text{Bulk density of bed in air}}{\text{Density of bed material}}$$

Dimensional Analysis

In considering the seven variables,

$$\Delta P,\ D_p,\ L_o,\ U_m,\ (\rho_s - \rho_f),\ \rho_f,$$

there are three dimensions involved, and therefore four dimensionless groups may be formed by analysis.

It may be written that

$$\Delta P \propto (\ D_p^{a},\ L_o^{b}\ U_m^{c}\ (\rho_s - \rho_f)^{d}\ \rho_f^{e}\ \mu^{f}) \qquad \text{- - - - - (a)}$$

where a, b, c, d, e and f are arbitrary indices.

In any dimensionally homogeneous equation it is axiomatic that the dimensions of mass, length and time, considered separately, should be the same on each side of the equation.

Considering dimensions of mass, the following expression is true:-

$$1 = d + e + f \qquad \text{- - - - - (b)}$$

Proceeding in the same way for dimensions of length:-

$$-1 = a + b + c - 3d - 3e - f \qquad \text{- - - - - (c)}$$

and for dimensions of time:-

$$-2 = -c - f \qquad \text{- - - - - (d)}$$

Since these three equations contain six unknowns, it is not possible to obtain a complete solution. Three of the unknowns may be expressed in terms of the remainder.

Solving (b), (c) and (d) for a, c and e:-

$$c = 2 - f$$

$$e = 1 - d - f$$

$$a = - f - b$$

Substituting these values in Equation (a)

$$\Delta P \propto D_p^{-f-b} . L_o^{b} . U_m^{2-f} (\rho_s - \rho_f)^{d} . \rho_f^{1-d-f} . \mu^{f}$$

$$\Delta P \propto (U_m^{2} . \rho_f) . \left(\frac{L_o}{D_p}\right)^{b} \left(\frac{\rho_s - \rho_f}{\rho_f}\right)^{d} \left(\frac{\mu}{D_p . U_m . \rho_f}\right)^{f}$$

or;-

$$\left(\frac{\Delta P}{U_m^{2} . \rho_f}\right) = f\left[\left(\frac{L_o}{D_p}\right); \left(\frac{\rho_s - \rho_f}{\rho_f}\right); \left(\frac{U_m . D_p . \rho_f}{\mu}\right)\right]$$

This is the final result obtainable by dimensional analysis. A further step may be taken, since other things being equal it is physically obvious that the pressure drop through a bed of material will be directly proportional to the depth of the bed, or that P is proportional to Lo.

This is corroborated by the experimental results plotted in Figure 28, (b).

Therefore:-

$$\left(\frac{D_p}{U_m^{2} . \rho_f} . \frac{\Delta P}{L_o}\right) = f\left[\left(\frac{\rho_s - \rho_f}{\rho_f}\right); \left(\frac{U_m . D_p . \rho_f}{\mu}\right)\right] \quad \text{------ (2)}$$

This simplification is also valid for the system when in a teetering condition, since it has already been seen (Figures 17 - 19 and 22 - 27) that when this condition is reached, the pressure drop remains constant irrespective of the rate of fluid flow. Figure 28 (a) shows this for medium sand.

It will be seen that the group $\frac{D_p}{U_m^{2} . \rho_f} . \left(\frac{\Delta P}{L_o}\right)$ is similar to a

friction factor as commonly used in the solution of fluid flow problems the difference being in the inclusion of a constant of 4/3 in the latter case.(11)

For the sake of uniformity it is proposed to include this constant and write the group as:-

$$\frac{4}{3} \frac{D_p}{U_m^2 \rho_f} \left(\frac{\Delta P}{L_o}\right)$$

Since, experimentally the differential head was actually measured in the tables which follow, these measurements have been given. In calculating the former group use has been made of the following relationship:-

$$\Delta P = \Delta H \times \rho_f \times g$$

so that the group now becomes

$$\frac{4}{3} \cdot \frac{D_p \, g}{U_m^2} \left(\frac{\Delta H}{L_o}\right)$$

This group is designated by the symbol ψ. for particles of constant shape and roughness

A plot of ψ against the Reynolds Number $(Re_m)_A$ should yield a curve of a particular but standard shape such that if any of the variables, as for example, the viscosity or density are changed, the new conditions of flow are represented by a point whose position on the standard curve, within the limits of experimental error still falls accurately on that curve.

Experimental data showing the depth of bed, fluid velocity, per cent. voidage, and pressure drop corrected for the pressure drop due to the resistance of the apparatus (p. 82) for all particles, together with the computed correlating groups, are given in Tables XLIX to LXXVII.

REFERENCE TABLES.

TABLE XLIX - Fine Sand.

D_p = 0.0099 in.; μ = 0.00071 lbs./ft.sec.; L_o = 5.83 cms.;
ρ_s = 2.653 g./ml.; ρ_f = 0.997 g./ml.; $\left(\frac{\Delta H}{L_o}\right)_{fl.}$ = 1.32

L (cms.)	Δ H (cms. water)	u_m (ft./sec.)	Re_m	$K_{\Delta H}$	ψ'	ψ	ϵ (per cent.)	f(ϵ)
9.4	0.0	0.0	-	-	-	-	38.0	-
9.6	7.7	0.00236	0.171	94	175	8,580	39.3	0.01737
10.5	7.7	0.01201	0.869	94	13.7	332	44.5	0.0972
16.2	8.3	0.02919	2.111	102	3.7	61.1	64.0	0.236
22.0	8.5	0.04175	3.019	104	5.42	30.5	75.9	0.3448
29.4	8.6	0.05242	3.792	105	5.8	19.5	80.2	0.4472
32.5	8.7	0.05569	4.027	107	6.15	17.6	82.1	0.668
40.1	8.7	0.0621	4.492	107	5.34	14.2	85.5	0.540
41.3	8.7	0.0628	4.540	107	5.92	13.9	85.9	0.5416

TABLE XLIX - Fine Sand (Cont'd.)

L (cms.)	ΔH (cms. water)	u_m (ft./sec.)	Re_m	$K_{\Delta H}$	ψ'	ψ	ϵ (per cent.)	$f(\epsilon)$
54.3	8.7	0.0689	4.984	107	4.97	11.5	89.3	0.6096
56.8	8.7	0.0707	5.111	107	5.27	10.9	89.7	0.6228
71.5	8.7	0.0768	5.560	107	4.84	9.2	91.8	0.6988
95.0	8.7	0.0827	5.982	107	4.45	7.9	93.9	0.7592

TABLE L - Fine Sand.

D_p = 0.0099 in.; μ = 0.00071 lbs./ft.sec.; L_o = 12.22 cms.;
ρ_s = 2.653 g./ml.; ρ_f = 0.997 g./ml.; $\left(\frac{\Delta H}{L_o}\right)_{fl.}$ = 1.17

L (cms.)	ΔH (cms. water)	u_m (ft./sec.)	Re_m	$K_{\Delta H}$	ψ'	ψ	ϵ (per cent.)	$f(\epsilon)$
17.7	0.0	0.0	-	-	-	-	31.0	-
17.9	8.5	0.001168	0.085	50	127.2	18,460	31.7	0.0156
17.9	14.0	0.002134	0.154	82	199.6	9,230	31.7	0.01766
19.7	15.2	0.008425	0.610	89	23.8	.639	38.0	0.070
29.0	16.0	0.0265	1.917	94	9.01	68.3	57.9	0.230
38.2	15.8	0.0355	2.568	92	8.0	37.3	68.0	0.3248
50.6	15.7	0.04763	3.447	92	6.1	20.6	75.9	0.4554
65.4	15.7	0.0563	4.073	92	5.4	14.8	87.3	0.4550
86.5	16.4	0.0639	4.623	96	6.0	14.0	85.9	0.618
101.0	17.0	0.0675	4.883	100	5.2	11.2	87.9	0.6348

TABLE LI - Fine Sand.

$D_p = 0.0099$ in.; $\mu = 0.00071$ lbs./ft.sec.; $L_o = 14.88$ cms.;
$\rho_s = 2.653$ g./ml.; $\rho_f = 0.997$ g./ml.; $\left(\frac{\Delta H}{L_o}\right)_{fl.} = 1.28$

L (cms.)	ΔH (cms. water)	u_m (ft./sec.)	Re_m	$K_{\Delta H}$	ψ'	ψ	ϵ (per cent.)	$f(\epsilon)$
24.0	0.0	0.0	-	-	-	-	38.0	-
24.0	16.5	0.00191	0.138	79	227.0	11,075	38.0	0.01752
25.5	19.8	0.00696	0.504	95	49.1	998	41.7	0.0532
43.7	22.0	0.02673	1.937	106	14.7	75.4	66.0	0.2056
58.8	22.5	0.04010	2.903	108	12.5	34.2	74.7	0.3188
82.0	22.5	0.05312	3.845	108	8.6	19.5	81.9	0.442
109.5	22.6	0.06267	4.534	109	6.3	14.2	86.5	0.5304

TABLE LII - Medium Sand.

D_p = 0.0174 in.; μ = 0.000629 lbs./ft.sec.; L_o = 12.23 cms.;
ρ_s = 2.654 g./ml/; ρ_f = 0.998 g./ml.; $\left(\frac{\Delta H}{L_o}\right)_{fl.}$ = 1.334

L (cms.)	ΔH (cms. water)	u_m (ft./sec.)	Re_m	$K_{\Delta H}$	ψ'	ψ	ϵ (per cent.)	f(ϵ)
19.7	0.0	0.0	-	-	-	-	37.9	-
19.7	1.7	0.000865	0.124	67	234.0	11,630	37.9	0.01737
19.7	3.8	0.002022	0.291	150	95.1	4,725	37.9	0.01844
19.7	6.2	0.003144	0.451	245	64.7	3,215	37.9	0.01836
19.7	8.2	0.004155	0.597	324	48.8	2,425	37.9	0.01856
19.7	10.6	0.005278	0.758	418	39.1	1,940	37.9	0.01872
19.7	12.5	0.006286	0.903	493	32.5	1,613	37.9	0.01924
19.7	14.0	0.007075	1.016	552	28.8	1,428	37.9	0.01940

TABLE LII - Medium Sand (Cont'd.)

L (cms.)	ΔH (cms. water)	u_m (ft./sec.)	Re_m	$K_{\Delta H}$	ψ'	ψ	ϵ (per cent.)	$f(\epsilon)$
19.7	15.8	0.007970	1.145	624	25.6	1,270	37.9	0.01970
20.5	16.5	0.01628	2.338	651	9.4	318	40.4	0.0416
21.0	16.9	0.02077	2.982	667	9.9	200	41.8	0.0530
21.0	17.0	0.02200	3.160	671	8.9	179	41.8	0.05694
22.5	17.3	0.02806	4.030	683	7.2	112	45.6	0.07306
24.5	17.5	0.03403	4.890	690	6.6	77.0	50.1	0.0922
26.3	17.5	0.04008	5.760	690	5.8	56.0	53.5	0.1126
27.5	17.3	0.04492	6.450	683	5.1	44.0	55.5	0.1302

TABLE LIII - Medium Sand.

D_p = 0.0174 in.; μ = 0.000629 lbs./ft.sec.; L_o = 18.57 cms.;
ρ_s = 2.654 g./ml.; ρ_f = 0.997 g./ml.; $\left(\frac{\Delta H}{L_o}\right)_{fl.}$ = 1.48

L (cms.)	Δ H (cms. water)	u_m (ft./sec.)	Re_m	$K_{\Delta H}$	ψ'	ψ	ϵ (per cent.)	f(ϵ)
29.9	0.0	0.0	-	-	-	-	38.7	-
29.9	4.6	0.00146	0.210	125	152.2	7,560	37.9	0.01614
29.9	8.5	0.002808	0.403	230	76.1	3,780	37.9	0.01641
29.9	14.5	0.00483	0.694	376	42.0	2,083	37.9	0.01832
29.9	17.3	0.005616	0.807	448	37.0	1,863	37.9	0.0177
29.9	23.8	0.007633	1.098	617	27.5	1,367	37.9	0.01902
30.6	27.2	0.00966	1.389	705	24.4	976	37.3	0.02062
31.0	26.8	0.01056	1.517	695	22.8	806	40.1	0.01354

TABLE LIII - Medium Sand (Cont'd.)

L (cms.)	ΔH (cms. water)	u_m (ft./sec.)	Re_m	$K_{\Delta H}$	ψ'	ψ	ϵ (per cent.)	$f(\epsilon)$
31.5	26.6	0.01213	1.744	689	19.8	605	41.1	0.02698
31.8	26.3	0.01527	2.195	682	13.2	378	41.6	0.03684
32.6	26.1	0.01774	2.550	676	9.3	218	43.0	0.05550
33.2	26.0	0.02044	2.937	674	10.4	209	44.1	0.0518
33.2	26.1	0.02258	3.245	676	8.5	171	44.1	0.0578
34.0	26.1	0.02258	3.245	676	10.2	171	45.4	0.0578
34.0	26.2	0.02404	3.445	679	9.7	153	45.4	0.06112
34.2	26.3	0.02493	3.584	682	9.2	142	45.7	0.06474
34.8	26.4	0.02684	3.856	684	8.4	123	46.6	0.0702

TABLE LIII - Medium Sand (Cont'd.)

L (cms.)	ΔH (cms. water)	u_m (ft./sec.)	Re_m	$K_{\Delta H}$	ψ'	ψ	ϵ (per cent.)	$f(\epsilon)$
35.3	26.4	0.02807	4.032	684	8.1	112.0	47.4	0.0721
36.0	26.5	0.0301	4.33	687	7.5	98.1	48.4	0.0798
36.8	26.6	0.03155	4.535	689	7.3	89.0	49.5	0.08506
37.2	26.7	0.03335	4.791	692	6.8	80.0	50.1	0.0896
38.1	26.7	0.0355	5.103	692	6.5	71.2	51.3	0.096
39.0	26.7	0.0355	5.103	692	7.5	71.2	53.8	0.096
39.3	26.7	0.0382	5.492	692	6.1	61.0	52.8	0.1062
41.3	26.8	0.0412	5.923	694	6.0	53.0	55.0	0.1156
42.0	26.8	0.0425	6.110	694	5.8	49.0	55.8	0.1210

TABLE LIII- Medium Sand (Cont'd.)

L (cms.)	ΔH (cms. water)	u_m (ft./sec.)	Re_m	$K_{\Delta H}$	ψ'	ψ	ϵ (per cent.)	$f(\epsilon)$
42.5	26.8	0.0427	6.14	694	5.9	49.0	56.3	0.1212
46.0	26.8	0.0511	7.35	694	4.7	34.1	59.7	0.1518
52.8	27.0	0.0617	8.875	700	4.4	24.0	64.7	0.1898
58.0	27.2	0.0702	10.09	705	3.8	18.0	68.0	0.2166
61.8	27.3	0.0765	11.05	708	3.5	15.0	70.0	0.2522
67.5	27.4	0.0832	11.96	710	3.4	13.1	72.5	0.2944
73.7	27.6	0.0914	13.14	715	3.1	11.1	74.8	0.3124
85.2	27.7	0.0987	14.20	718	3.3	10.1	78.2	0.3472

TABLE LIV - Medium Sand.

D_p = 0.0174 in.; μ = 0.000692 lbs./ft.sec.; L_o = 25.4 cms.;
ρ_s = 2.654 g./ml.; ρ_f = 0.998 g./ml.; $\left(\frac{\Delta H}{L_o}\right)_{fl.}$ = 1.461

L (cms.)	ΔH (cms. water)	u_m (ft./sec.)	Re_m	$K_{\Delta H}$	ψ'	ψ	ϵ (per cent.)	f (ϵ)
40.9	0.0	0.0	-	-	-	-	37.9	-
40.9	6.0	0.00149	0.195	99	140.2	6,960	37.9	0.01954
40.9	11.0	0.00261	0.341	173	79.9	3,970	37.9	0.01818
40.9	15.0	0.00355	0.463	236	59.2	2,940	37.9	0.01938
40.9	17.8	0.00418	0.456	280	72.3	3,595	37.9	0.01642
41.0	23.5	0.00555	0.724	369	39.0	1,878	38.1	0.01996
41.1	26.9	0.00628	0.820	423	35.4	1,678	38.2	0.02262
41.2	30.0	0.00702	0.916	471	32.7	1,498	38.4	0.02070

TABLE LIV - Medium Sand (Cont'd.)

L (cms.)	$\triangle H$ (cms. water)	u_m (ft./sec.)	Re_m	$K_{\triangle H}$	ψ'	ψ	ϵ (per cent.)	$f(\epsilon)$
41.3	35.8	0.00829	1.082	562	28.4	1,282	38.5	0.02184
41.2	37.0	0.00885	1.155	581	25.4	1,163	38.4	0.02142
42.7	36.7	0.01102	1.438	576	22.4	744	40.5	0.02758
45.2	36.8	0.01786	2.331	578	16.2	284	43.8	0.04650
49.7	36.9	0.0273	3.563	580	9.7	122	48.9	0.07466
54.0	37.0	0.0345	4.503	581	7.7	76	53.0	0.09946
58.9	37.2	0.0412	5.380	584	6.8	54	56.9	0.1226
62.0	37.3	0.0467	6.093	585	5.9	42	59.1	0.1428

TABLE LIV - Medium Sand (Cont'd.)

L (cms.)	$\triangle H$ (cms. water)	u_m (ft./sec.)	Re_m	$K_{\triangle H}$	ψ'	ψ	ϵ (per cent.)	$f(\epsilon)$
66.6	37.7	0.0527	6.880	592	5.3	33.0	61.9	0.1650
70.5	37.9	0.0576	7.520	598	5.0	28.2	64.0	0.1826
74.5	38.2	0.0623	8.130	600	4.6	24.2	65.9	0.1984
77.8	38.5	0.0667	8.705	604	4.4	21.3	67.4	0.2164
82.2	38.7	0.0711	9.280	607	4.2	18.8	69.1	0.234
86.5	38.8	0.0757	9.880	609	4.0	16.7	70.7	0.2524
90.8	39.1	0.0795	10.380	614	4.1	16.0	72.1	0.2530

TABLE LV - Medium Sand.

$D_p = 0.0174$ in.; $\mu = 0.000728$ lbs./ft.sec.; $L_o = 31.3$ cms.;
$\rho_s = 2.654$ g./ml.; $\rho_f = 0.999$ g./ml.; $\left(\frac{\Delta H}{L_o}\right)_{fl.} = 1.51$

L (cms.)	ΔH (cms. water)	u_m (ft./sec.)	Re_m	$K_{\Delta H}$	ψ'	ψ	ϵ (per cent.)	$f(\epsilon)$
50.4	0.0	0.0	-	-	-	-	38.0	-
50.4	24.5	0.00484	0.601	282	42.0	2,084	37.9	0.0216
50.6	31.7	0.00631	0.784	365	33.5	1,585	38.2	0.02208
50.7	37.0	0.00724	0.900	426	30.0	1,402	38.3	0.02212
50.8	40.5	0.00798	0.991	466	27.7	1,267	38.4	0.02252
51.0	45.0	0.00881	1.094	518	26.0	1,155	38.6	0.02268
52.3	46.4	0.01101	1.368	534	21.8	762	40.2	0.02824
53.2	46.2	0.01271	1.579	533	19.0	570	41.2	0.03312
55.4	46.0	0.01613	2.004	530	16.2	352	43.5	0.0426

TABLE LV - Medium Sand (Cont'd.)

L (cms.)	ΔH (cms. water)	u_m (ft./sec.)	Re_m	$K_{\Delta H}$	ψ'	ψ	ϵ (per cent.)	$f(\epsilon)$
58.8	45.8	0.0218	2.708	528	13.4	192	46.8	0.0604
64.8	46.1	0.0303	3.765	531	9.4	100	51.7	0.088
69.5	46.4	0.03695	4.590	535	7.7	67.8	55.0	0.122
75.7	46.8	0.0436	5.147	539	7.5	54.3	58.7	0.1272
80.7	47.1	0.04875	6.057	543	6.2	39.5	61.2	0.152
85.3	47.4	0.0538	6.684	546	5.6	32.6	63.3	0.1718
90.7	47.8	0.0593	7.367	551	5.2	27.1	65.5	0.1918
96.0	48.3	0.0651	8.088	557	4.8	22.8	67.4	0.2154
101.0	48.5	0.0691	8.587	559	4.5	20.3	69.0	0.2296
106.5	48.7	0.0742	9.216	561	4.2	17.6	70.7	0.250

TABLE LVI - Medium Sand.

D_p = 0.0174 in.; μ = 0.000676 lbs./ft.sec.; L_o = 38.1 cms.;
ρ_s = 2.654 g./ml.; ρ_f = 0.998 g./ml.; $\left(\frac{\Delta H}{L_o}\right)_{fl.}$ = 1.5

L (cms.)	ΔH (cms. water)	u_m (ft./sec.)	Re_m	$K_{\Delta H}$	ψ'	ψ	ϵ (per cent.)	$f(\epsilon)$
61.4	0.0	0.0	-	-	-	-	38.0	-
61.4	7.3	0.001234	0.165	80	159.2	7,845	38.0	0.01346
61.4	8.3	0.00292	0.390	200	72.1	3,510	38.0	0.01738
61.4	27.5	0.00419	0.560	301	52.6	2,560	38.0	0.01876
61.3	31.1	0.004795	0.641	340	44.5	2,207	37.9	0.01948
61.3	36.7	0.00564	0.754	402	38.0	1,888	37.9	0.0196
61.4	42.0	0.00637	0.851	460	34.9	1,695	38.0	0.01956
61.4	44.3	0.00668	0.892	485	33.4	1,627	38.0	0.01908
61.5	49.0	0.00757	0.984	536	30.8	1,478	38.1	0.01828

TABLE LVI - Medium Sand (Cont'd.)

L (cms.)	ΔH (cms. water)	u_m (ft./sec.)	Re_m	$K_{\Delta H}$	ψ'	ψ	ϵ (per cent.)	$f(\epsilon)$
61.7	53,0	0.00797	1.064	580	29.4	1,368	38.3	0.0194
63.2	56.6	0.01039	1.388	620	22.9	859	39.7	0.02468
70.5	56.2	0.01987	2.654	615	15.0	233	46.0	0.05066
79.2	56.7	0.0302	4.033	621	9.7	102	51.9	0.0866
85.3	56.8	0.0367	4.901	622	8.0	69.0	55.3	0.1030
88.3	56.9	0.0408	5.450	623	7.0	56.0	56.9	0.1152
94.2	57.2	0.0467	6.237	627	6.2	43.0	59.6	0.1348
100.5	57.4	0.0527	7.040	629	5.3	33.9	62.1	0.1534
106.5	57.8	0.0578	7.720	633	4.3	28.4	64.3	0.1764

TABLE LVII - Coarse Sand.

D_p = 0.028 in.; μ = 0.00066 lbs./ft.sec.; L_o = 13.1 cms.;
ρs = 2.655 g./ml.; ρf = 0.998 g./ml.; $\left(\frac{\Delta H}{L_o}\right)_{fl.}$ = 1.37

L (cms.)	ΔH (cms. water)	u_m (ft./sec.)	Re_m	$K_{\Delta H}$	ψ'	ψ	ϵ (per cent.)	$f(\epsilon)$
20.4	0.0	0.0	-	-	-	-	-	-
20.4	8.4	0.00833	1.835	1170	13.3	927	35.8	0.01758
20.4	13.2	0.0135	2.972	1840	8.0	556	35.8	0.01944
20.4	16.1	0.01692	3.725	2240	5.9	431	35.5	0.02042
20.9	17.2	0.02136	4.702	2390	5.3	289	37.3	0.02530
21.3	16.3	0.02924	6.440	2270	3.3	146	38.5	0.03904
21.9	16.7	0.03504	7.710	2330	3.0	104.5	40.2	0.0488
22.9	17.5	0.04233	9.320	2440	2.7	75.5	42.8	0.05870
23.8	18.4	0.04885	10.760	2560	3.7	59.0	45.0	0.0678
24.5	18.9	0.05268	11.602	2630	3.6	52.0	46.5	0.07310

TABLE LVII - Coarse Sand (Cont'd.)

L (cms.)	ΔH (cms. water)	u_m (ft./sec.)	Re_m	$K_{\Delta H}$	ψ'	ψ	ϵ (per cent.)	$f(\epsilon)$
25.3	19.5	0.05818	12.815	2710	3.4	44.0	48.2	0.0806
26.5	19.8	0.06312	13.910	2760	3.3	38.0	50.6	0.08786
27.3	20.0	0.0674	14.800	2790	3.3	34.0	52.0	0.0942
27.8	19.9	0.0721	15.880	2770	2.9	29.5	52.3	0.1052
28.8	19.7	0.0767	16.900	2740	2.8	25.5	54.5	0.1156
29.9	19.4	0.08007	17.640	2700	2.8	23.0	56.2	0.1262
30.8	18.7	0.08503	18.730	2600	2.6	20.0	57.5	0.1376
31.7	17.9	0.09007	19.840	2490	2.3	17.0	58.7	0.1558
32.5	17.2	0.0936	20.610	2390	2.2	15.0	59.7	0.1732
33.1	16.4	0.0967	21.300	2280	2.0	13.5	60.5	0.1874

TABLE LVIII - Coarse Sand.

D_p = 0.028 in.; μ = 0.000692 lbs./ft.sec.; L_o = 19.6 cms.;
ρs = 2.655 g./ml.; ρf = 0.998 g./ml.; $\left(\frac{\Delta H}{L_o}\right)_{fl.}$ = 1.39

L (cms.)	ΔH (cms. water)	u_m (ft./sec.)	Re_m	$K_{\Delta H}$	ψ'	ψ	ϵ (per cent.)	$f(\epsilon)$
30.5	0.0	0.0	-	-	-	-	35.8	-
30.5	11.3	0.00631	1.325	956	20.9	1,453	35.8	0.0148
30.5	14.6	0.00966	2.208	1235	9.7	677	35.8	0.02056
30.5	19.6	0.01303	2.736	1657	8.5	591	35.8	0.01946
30.5	23.5	0.0155	3.255	1987	7.2	500	35.8	0.01978
30.5	26.2	0.0174	3.653	2216	6.1	443	35.6	0.02032
30.9	27.0	0.0195	4.093	2283	5.9	364	36.6	0.02256
32.3	26.7	0.0262	5.500	2257	5.0	199	39.3	0.0326
33.4	26.8	0.0325	6.820	2267	4.4	130	41.3	0.04234

TABLE LVIII - Coarse Sand (Cont'd.)

L (cms.)	ΔH (cms. water)	u_m (ft./sec.)	Re_m	$K_{\Delta H}$	ψ'	ψ	ϵ (per cent.)	$f(\epsilon)$
35.2	27.3	0.0402	8.440	2308	4.5	87.0	44.3	0.05990
36.2	27.8	0.0458	9.620	2350	4.5	68.0	45.9	0.06376
37.4	28.0	0.0506	10.630	2367	4.1	56.0	47.6	0.07144
38.5	28.3	0.0552	11.590	2393	3.8	47.5	49.1	0.0800
40.3	28.7	0.0614	12.890	2427	3.5	38.0	51.4	0.0910
41.4	28.7	0.0656	13.770	2427	3.4	34.0	52.7	0.0986
42.8	28.8	0.0697	14.640	2436	3.3	30.5	54.2	0.1062
44.3	28.8	0.0749	15.720	2436	3.1	26.5	55.8	0.1170
46.0	28.9	0.0783	16.440	2444	3.1	24.0	57.4	0.1250
47.0	28.9	0.0822	17.250	2444	3.0	22.0	58.3	0.1318

TABLE LIX - Coarse Sand.

D_p = 0.028 in.; μ = 0.000692 lbs./ft.sec.; L_o = 26.8 cms.;
ρ_s = 2.655 g./ml.; ρ_f = 0.998 g./ml.; $\left(\frac{\Delta H}{L_o}\right)_{fl.}$ = 1.41

L (cms.)	ΔH (cms. water)	u_m (ft./sec.)	Re_m	$K_{\Delta H}$	ψ'	ψ	ϵ (per cent.)	$f(\epsilon)$
41.7	0.0	0.0	-	-	-	-	35.7	-
41.7	9.3	0.00505	1.060	576	19.2	1,369	35.7	0.01974
41.6	14.6	0.00764	1.603	904	13.0	939	35.6	0.01950
41.6	19.4	0.00977	2.051	1200	10.6	761	35.6	0.01944
41.6	24.9	0.01224	2.568	1540	8.6	623	35.6	0.01926
41.6	29.2	0.01404	2.946	1807	7.5	556	35.4	0.01944
41.6	33.7	0.01583	3.323	2086	6.8	505	35.4	0.02022
41.6	37.4	0.01965	4.124	2314	5.0	363	35.6	0.0226
43.0	37.0	0.02358	4.950	2290	4.8	249	37.7	0.02848

TABLE LIX - Coarse Sand (Cont'd.)

L (cms.)	ΔH (cms. water)	u_m (ft./sec.)	Re_m	$K_{\Delta H}$	ψ'	ψ	ϵ (per cent.)	$f(\epsilon)$
44.4	36.9	0.0283	5.940	2282	4.6	173	39.7	0.03074
46.4	37.3	0.0356	7.470	2308	4.3	111	42.2	0.04616
48.3	37.6	0.0414	8.690	2326	4.3	82.0	44.5	0.05612
50.3	38.0	0.0476	9.990	2352	4.1	63.0	45.8	0.06588
52.5	38.4	0.0534	11.210	2376	3.3	50.5	49.0	0.07324
54.3	38.7	0.0587	12.320	2395	3.4	42.0	50.7	0.0858
56.5	38.9	0.0648	13.600	2407	3.1	34.5	52.6	0.1102
59.0	38.9	0.0706	14.820	2407	3.3	29.5	54.6	0.1084
61.3	38.8	0.0751	15.760	2401	3.2	26.0	56.3	0.1184
63.0	38.7	0.0803	16.850	2395	2.9	22.5	57.5	0.1310

TABLE LX - Coarse Sand.

D_p = 0.028 in.; μ = 0.000676 lbs./ft.sec.; L_o = 32.6 cms.;
ρ_s = 2.655 g./ml.; ρ_f = 0.998 g./ml.; $\left(\frac{\Delta H}{L_o}\right)_{fl.}$ = 1.43

L (cms.)	ΔH (cms. water)	u_m (ft./sec.)	Re_m	$K_{\Delta H}$	ψ'	ψ	ϵ (per cent.)	$f(\epsilon)$
50.7	0.0	0.0	-	-	-	-	35.7	-
50.7	16.2	0.005995	1.290	863	19.4	1,384	35.7	0.01626
50.7	19.5	0.00842	1.810	1038	11.9	846	35.7	0.01952
50.7	24.0	0.01011	2.175	1278	10.2	722	35.7	0.01954
50.7	33.0	0.01346	2.894	1757	7.9	560	35.7	0.01946
50.7	37.8	0.01505	3.235	2013	7.1	514	35.7	0.01930
50.9	42.7	0.01662	3.573	2274	6.9	475	35.9	0.01948
50.9	46.4	0.01954	4.200	2470	5.4	374	35.8	0.02196

TABLE LX - Coarse Sand (Cont'd.)

L (cms.)	ΔH (cms. water)	u_m (ft./sec.)	Re_m	$K_{\Delta H}$	ψ'	ψ	ϵ (per cent.)	$f(\epsilon)$
53.3	46.2	0.02516	5.410	2460	5.2	225	38.8	0.0294
56.7	46.3	0.03436	7.390	2465	6.3	121	42.5	0.0432
60.0	46.7	0.04312	9.275	2486	5.0	77.0	45.7	0.0572
63.1	47.1	0.05077	10.290	2507	4.8	63.0	48.3	0.0650
67.0	47.4	0.0572	12.300	2524	4.1	45.0	51.4	0.0808
69.8	47.7	0.06323	13.600	2540	3.7	36.5	53.3	0.0932
73.8	47.9	0.0712	15.310	2551	3.4	29.0	55.8	0.1070
76.2	48.0	0.07695	16.540	2556	3.2	25.0	57.2	0.1200

TABLE LXI - Coarse Sand.

D_p = 0.028 in.; μ = 0.000644 lbs./ft.sec.; L_o = 38.8 cms.;
ρ_s = 2.655 g./ml.; ρ_f = 0.998 g./ml.; $\left(\frac{\Delta H}{L_o}\right)_{fl.}$ = 1.42

L (cms.)	ΔH (cms. water)	u_m (ft./sec.)	Re m	$K_{\Delta H}$	ψ'	ψ	ϵ (per cent.)	$f(\epsilon)$
60.2	0.0	0.0	-	-	-	-	35.7	-
60.2	16.0	0.004042	0.912	493	22.2	1,583	35.7	0.01926
60.2	5.8	0.002336	0.527	286	32.8	2,335	35.7	0.02228
60.2	14.0	0.005391	1.217	690	17.2	1,243	35.6	0.01890
60.2	23.8	0.00893	2.106	1174	9.8	707	35.6	0.02036
60.2	35.0	0.01258	2.840	1726	7.9	571	35.6	0.01962
60.2	38.7	0.01370	3.092	1908	7.4	533	35.6	0.01944
60.4	55.1	0.01932	4.360	2717	5.5	382	35.8	0.02070
62.4	54.8	0.02336	5.270	2703	5.2	260	37.8	0.02578

TABLE LXI - Coarse Sand (Cont'd.)

L (cms.)	ΔH (cms. water)	u_m (ft./sec.)	Re_m	$K_{\Delta H}$	ψ'	ψ	ϵ (per cent.)	$f(\epsilon)$
65.5	54.9	0.0310	7.000	2707	4.6	148	40.8	0.0366
67.0	55.1	0.0337	7.610	2717	4.7	125	42.1	0.0400
70.3	55.6	0.0402	9.070	2742	4.9	89.0	44.8	0.04944
73.3	56.1	0.0462	10.430	2767	5.0	68.0	47.1	0.0588
74.2	56.4	0.0519	11.720	2782	4.0	54.0	47.7	0.0694
77.2	56.6	0.0574	12.96	2792	3.9	44.5	49.8	0.0788
79.7	56.8	0.0618	13.95	2802	3.5	38.5	51.3	0.0858
82.0	56.9	0.0655	14.78	2807	3.4	34.5	52.7	0.0928
84.5	57.1	0.0700	15.80	2816	3.2	30.0	54.1	0.1034

TABLE LXII - Coarse Sand.

$D_p = 0.028$ in.; $\mu = 0.000644$ lbs./ft.sec.; $L_o = 45.4$ cms.;
$\rho_s = 2.655$ g./ml.; $\rho_f = 0.998$ g./ml.; $\left(\frac{\Delta H}{L_o}\right)_{fl.} = 1.49$

L (cms.)	ΔH (cms. water)	u_m (ft./sec.)	Re_m	$K_{\Delta H}$	ψ'	ψ	ϵ (per cent.)	$f(\epsilon)$
70.6	0.0	0.0	-	-	-	-	35.7	-
70.6	12.7	0.00382	0.862	535	27.0	1,920	35.7	0.01668
70.6	23.5	0.00708	1.597	990	14.6	1,036	35.7	0.01786
70.6	29.0	0.00854	1.927	1222	12.3	878	35.7	0.01790
70.6	36.0	0.01056	2.382	1517	10.0	713	35.7	0.01824
70.6	43.0	0.01235	2.786	1812	8.8	623	35.7	0.01846
70.6	49.5	0.01404	3.166	2085	7.8	556	35.7	0.01856

TABLE LXII - Coarse Sand (Cont'd,)

L (cms.)	ΔH (cms. water)	u_m (ft./sec.)	Re_m	$K_{\Delta H}$	ψ'	ψ	ϵ (per cent.)	$f(\epsilon)$
70.6	57.7	0.01606	3.625	2430	6.9	494	35.7	0.01844
70.6	64.8	0.01774	4.000	2730	6.4	455	35.7	0.01824
75.0	65.0	0.0264	5.960	2739	5.3	206	39.5	0.02970
78.4	65.3	0.03235	7.300	2752	5.2	138	42.1	0.0384
83.0	65.8	0.04042	9.120	2774	5.2	89.0	45.3	0.0500
86.9	66.2	0.04718	10.640	2790	4.9	66.0	47.8	0.0606
91.3	66.6	0.05425	12.240	2806	4.3	50.0	50.3	0.072
95.1	66.9	0.0601	13.560	2820	4.0	41.0	52.3	0.0828

TABLE LXIII - Coarse Sand.

$D_p = 0.028$ in.; $\mu = 0.000660$ lbs./ft.sec.; $L_o = 51.3$ cms.;
$\rho_s = 2.655$ g./ml.; $\rho_f = 0.998$ g./ml.; $\left(\frac{\Delta H}{L_o}\right)_{fl.} = 1.49$

L (cms.)	ΔH (cms. water)	u_m (ft./sec.)	Re_m	$K_{\Delta H}$	ψ'	ψ	ϵ (per cent.)	$f(\epsilon)$
79.8	0.0	0.0	-	-	-	-	35.7	-
79.8	21.0	0.00494	1.089	746	23.6	1,680	35.7	0.0156
79.9	31.0	0.00708	1.560	1101	17.3	1,208	35.8	0.01556
79.9	34.0	0.00764	1.684	1208	16.3	1,137	35.8	0.01556
79.9	41.0	0.00910	2.006	1456	13.9	966	35.8	0.01554
79.9	47.2	0.01033	2.275	1677	12.4	865	35.8	0.01574
79.9	57.2	0.01212	2.670	2032	10.9	760	35.8	0.01552

TABLE LXIII - Coarse Sand (Cont'd.)

L (cms.)	ΔH (cms. water)	u_m (ft./sec.)	Re_m	$K_{\Delta H}$	ψ'	ψ	ϵ (per cent.)	$f(\epsilon)$
80.1	66.5	0.01382	3.045	2362	10.0	679	36.0	0.01398
81.4	76.0	0.01538	3.390	2700	10.8	627	37.0	0.0150
85.6	75.4	0.02392	5.270	2678	6.8	258	40.1	0.02604
90.0	75.4	0.03032	6.680	2678	6.6	160	43.0	0.03470
96.3	76.0	0.0399	8.790	2700	6.6	93.5	46.7	0.0492
101.2	76.5	0.0468	10.320	2717	5.5	68.0	49.3	0.06030
106.3	77.1	0.0532	11.720	2739	5.0	53.0	51.8	0.07074

TABLE LXIV - Fine Galena

D_p = 0.0099 in.; μ = 0.00071 lbs./ft.sec.; L_o = 5.4 cms.;

ρs = 6.58 g./ml.; ρf = 0.999 g./ml.; $(\frac{\Delta H}{L_o})_{fl.}$ = 4.11

L (cms.)	Δ H (cms.water)	u_m (ft./sec.)	Re_m	$K_{\Delta H}$	ψ'	ψ	ϵ (per cent.)	f(ϵ)
10.4	0.0	0.0	-	-	-	-	48.1	-
10.4	8.4	0.00528	0.383	110	51.7	1991	48.1	0.03468
10.4	17.1	0.01045	0.758	223	26.9	1036	48.1	0.03528
10.4	21.8	0.01325	0.961	284	20.8	803	48.1	0.03614
10.5	20.8	0.03032	2.200	271	4.9	149	48.9	0.0936
10.8	20.6	0.02493	1.809	269	6.3	219	50.0	0.07530
11.0	21.4	0.03515	2.550	279	4.2	115	51.0	0.1048
11.0	22.4	0.04221	3.063	292	3.1	83.0	51.0	0.12650
11.3	22.9	0.0486	3.526	299	6.9	64.0	52.2	0.150
11.3	23.5	0.05522	4.008	306	5.5	51.0	52.2	0.1628
12.7	23.8	0.05896	4.276	310	6.6	45.5	57.5	0.1736
12.5	23.9	0.0621	4.507	312	5.7	41.0	56.8	0.1854
12.7	23.9	0.0621	4.533	312	5.9	40.5	57.5	0.1864

TABLE LXIV (Continued)

L (cms.)	ΔH (cms.water)	u_m (ft./sec.)	Re_m	$K_{\Delta H}$	ψ'	ψ	ϵ (per cent.)	$f(\epsilon)$
13.5	24.0	0.0678	4.920	313	5.7	34.5	60.0	0.206
13.5	24.0	0.0667	4,840	313	5.8	35.5	60.0	0.2030
14.2	24.2	0.0737	5.350	316	5.4	29.5	62.0	0.2272
13.0	24.1	0.0703	5.100	314	4.9	32.0	58.5	0.216
14.0	24.3	0.0744	5.400	317	5.1	29.0	61.5	0.2276
14.5	24.6	0.0794	5.760	321	4.9	26.0	62.8	0.2424
14.8	24.8	0.0820	5.950	324	4.8	24.5	63.6	0.2492
15.3	25.0	0.0857	6.220	326	4.6	22.5	64.7	0.2622
16.0	24.8	0.0833	6.040	323	5.2	23.5	66.3	0.2424
15.3	24.9	0.0856	6.210	324	4.6	22.5	64.7	0.2624
16.0	25.2	0.0902	6.540	328	4.6	20.5	66.3	0.278
16.5	25.2	0.0912	6.620	329	4.6	20.0	67.3	0.2800
17.5	25.5	0.0976	7.080	333	4.5	17.8	69.2	0.2986
18.0	25.5	0.0974	7.210	333	4.4	17.0	70.0	0.3090
19.0	25.6	0.102	7.400	334	4.6	16.3	71.6	0.3200

TABLE LXV - Fine Galena

D_p = 0.0099 in.; μ = 0.000747 lbs./ft.sec.; L_o = 11.2 cms.;

ρ_s = 6.58 g./ml.; ρ_f = 0.999 g./ml.; $(\frac{\Delta H}{L_o})_{fl.}$ = 4.55

L (cms.)	ΔH (cms.water)	u_m (ft./sec.)	Re_m	$K_{\Delta H}$	ψ'	ψ	ϵ (per cent.)	$f(\epsilon)$
21.8	0.0	0.0	-	-	-	-	48.7	-
21.8	14.2	0.00382	0.263	80	86.5	3085	48.7	0.03250
21.8	21.3	0.00573	0.395	120	57.6	2053	48.7	0.03266
21.8	30.2	0.00853	0.588	170	36.8	1313	48.7	0.03490
21.8	34.9	0.00988	0.681	197	31.7	1131	48.7	0.0354
21.8	40.5	0.0119	0.820	228	25.4	906	48.7	0.0376
22.5	45.6	0.02077	1.398	257	11.8	351	50.2	0.05984
22.0	49.6	0.01528	1.053	279	19.8	672	49.1	0.0402
22.5	45.8	0.02527	1.742	258	7.6	227	50.2	0.0750
23.2	48.1	0.0348	2.397	271	5.1	126	51.7	0.10230
26.1	49.9	0.0451	3.109	281	11.0	78.0	57.1	0.1330
28.4	51.1	0.0529	3.645	288	9.8	58.0	60.6	0.1552
31.3	51.9	0.0618	4.260	292	8.7	43.0	64.3	0.1838
30.0	51.9	0.0611	4.210	292	8.3	44.0	62.7	0.1806

TABLE LXV (Continued)

L (cms.)	ΔH (cms. water)	u_m (ft./sec.)	Re_m	$K_{\Delta H}$	ψ'	ψ	ϵ (per cent.)	$f(\epsilon)$
33.5	52.2	0.0689	4.750	294	7.9	35.0	66.6	0.2086
33.0	52.2	0.0678	4.670	294	7.9	36.0	66.1	0.2028
35.0	52.0	0.0748	5.160	293	7.1	29.5	68.0	0.2000
38.0	51.7	0.0813	5.600	291	6.7	25.0	70.5	0.256
41.0	51.5	0.0876	6.040	290	6.1	21.0	72.7	0.286
43.0	51.2	0.0937	6.460	289	5.7	18.5	74.0	0.308

TABLE LXVI - Fine Galena

D_p = 0.0099 in.; μ = 0.000728 lbs./ft.sec.; L_o = 13.5 cms.;

ρs = 6.58 g./ml.; ρf = 0.999 g./ml.; $(\frac{\Delta H}{L_o})_{fl.}$ = 4.53

L (cms.)	ΔH (cms.water)	u_m (ft./sec.)	Re_m	$K_{\Delta H}$	ψ'	ψ	ϵ (per cent.)	f(ϵ)
26.2	0.0	0.0	-	-	-	-	48.5	-
26.2	13.1	0.002695	0.191	65	129.3	4718	48.5	0.0282
26.2	23.2	0.00472	0.334	115	75.0	2739	48.5	0.02848
26.3	38.3	0.0082	0.580	189	41.9	1495	48.7	0.03110
26.4	49.6	0.0109	0.771	244	31.4	1095	48.9	0.03252
26.6	59.4	0.01348	0.953	293	25.6	859	49.2	0.03432
26.3	60.5	0.01202	0.850	298	31.6	1101	48.7	0.03000
26.7	61.2	0.01438	1.017	302	23.8	778	49.4	0.03536
26.8	61.2	0.0146	1.033	302	23.6	755	49.6	0.03644
26.3	65.0	0.01303	0.922	320	28.9	1005	48.7	0.03038
27.8	56.3	0.02392	1.691	278	10.0	259	51.4	0.0676
27.2	60.8	0.01483	1.048	300	25.0	728	50.4	0.03710
26.9	57.9	0.01584	1.120	285	19.4	607	49.8	0.04206

TABLE LXVI (Continued)

L (cms.)	ΔH (cms.water)	u_m (ft.sec.)	Re_m	$K_{\Delta H}$	ψ'	ψ	ϵ (per cent.)	$f(\epsilon)$
28.0	57.8	0.02842	2.010	285	7.5	185	51.8	0.0812
29.5	60.0	0.03594	2.540	296	6.5	122	54.2	0.1000
32.5	61.7	0.04399	3.104	304	7.1	84.5	58.5	0.12190
36.0	62.9	0.0526	3.720	310	11.0	59.5	62.5	0.148
39.9	63.5	0.0604	4.270	313	10.0	45.5	66.2	0.1736
42.5	63.7	0.0675	4.770	314	8.9	37.0	68.3	0.196
45.5	63.8	0.0742	5.250	315	8.1	30.5	70.3	0.2196
48.5	63.9	0.0811	5.730	315	7.3	25.5	72.3	0.2452
51.5	64.0	0.0856	6.050	316	7.0	23.0	73.8	0.2608

TABLE LXVII - Medium Galena

D_p = 0.0174 in.; μ = 0.00066 lbs./ft.sec.; L_o = 9.9 cms.;

ρ s = 6.47 g./ml.; ρ f = 0.998 g./ml.; $(\frac{\Delta H}{L_o})_{fl.}$ = 6.01

L (cms.)	ΔH (cms.water)	u_m (ft./sec.)	Re_m	$K_{\Delta H}$	ψ'	ψ	ϵ (per cent.)	$f(\epsilon)$
19.9	0.0	0.0	-	-	-	-	50.3	-
19.9	11.5	0.00741	1.014	508	44.8	1318	50.3	0.02110
19.8	11.0	0.00708	0.969	486	45.2	1380	50.0	0.02102
19.8	13.8	0.00865	1.184	610	38.0	1161	50.0	0.02086
19.8	18.0	0.01067	1.460	796	32.7	997	50.0	0.02008
19.8	23.8	0.01336	1.828	1052	27.5	841	50.0	0.0194
19.8	29.7	0.0156	2.134	1312	25.2	769	50.0	0.01862
19.8	35.8	0.01763	2.412	1582	23.8	726	50.0	0.01750
20.0	41.3	0.0256	3.504	1825	13.8	397	50.5	0.02316
20.8	48.3	0.0337	4.610	2134	11.6	268	52.4	0.02762
21.7	47.0	0.0410	5.610	2077	9.6	176	54.4	0.03608
27.2	44.2	0.0471	6.440	1952	7.7	126	55.4	0.0458
22.8	43.3	0.0558	7.630	1913	6.0	87.5	56.6	0.05772
23.0	43.3	0.0640	8.760	1913	4.8	66.5	57.0	0.0692

TABLE LXVII (Continued)

L (cms.)	ΔH (cms. water)	u_m (ft./sec.)	Re_m	$K_{\Delta H}$	ψ'	ψ	ϵ (per cent.)	$f(\epsilon)$
23.5	43.3	0.0694	9.500	1913	4.5	56.5	57.9	0.0766
24.0	43.3	0.0763	10.440	1913	4.1	47.0	58.8	0.0852
23.8	43.3	0.0641	8.770	1913	5.5	66.5	58.4	0.0692
24.0	43.3	0.0702	9.610	1913	4.8	55.5	58.8	0.07750
24.5	43.3	0.0776	10.620	1913	4.3	45.5	59.6	0.0878
26.0	43.3	0.0861	11.780	1913	4.4	37.0	61.9	0.1014
26.0	43.3	0.0928	12.700	1913	3.7	31.5	61.9	0.1126

TABLE LXVIII - Medium Galena

D_p = 0.0174 in.; μ = 0.000684 lbs./ft.sec.; L_o = 15.4 cms.;
ρs = 6.47 g./ml.; ρf = 0.998 g./ml.; $(\frac{\Delta H}{L_o})_{fl.}$ = 5.22

L (cms.)	ΔH (cms.water)	u_m (ft./sec.)	Re_m	$K_{\Delta H}$	Ψ'	Ψ	ϵ (per cent.)	$f(\epsilon)$
30.7	0.0	0.0	-	-	-	-	50.0	-
30.7	17.6	0.00876	1.158	466	30.3	927	50.0	0.02668
30.7	34.1	0.0166	2.192	901	16.4	501	50.0	0.02794
30.8	44.8	0.02268	2.996	1184	11.5	352	50.0	0.03012
31.3	40.0	0.02284	3.017	1058	11.2	310	50.8	0.03356
31.2	49.5	0.02684	3.545	1308	9.8	279	50.6	0.03316
31.3	57.0	0.03065	4.050	1507	8.8	245	50.8	0.02818
31.4	65.9	0.0346	4.570	1742	8.2	223	51.0	0.03372
31.5	71.1	0.03662	4.837	1880	8.0	215	51.1	0.03312
32.7	68.6	0.0423	5.590	1814	7.1	155	52.9	0.04130
34.2	72.9	0.0486	6.420	1927	7.3	125	55.0	0.0462
35.5	68.6	0.0617	8.150	1819	5.0	73.0	56.6	0.0662
37.0	69.3	0.0692	9.140	1832	4.9	58.5	58.4	0.0758
38.0	69.1	0.0771	10.190	1827	4.4	47.0	59.5	0.0872
39.0	69.5	0.0837	11.060	1838	4.1	40.0	60.5	0.0970

TABLE LXIX - Medium Galena

D_p = 0.0174 in.; μ = 0.00071 lbs./ft.sec.; L_o = 20.0 cms.;

ρ s = 6.47 g./ml.; ρ f = 0.999 g./ml.; $\left(\frac{\Delta H}{L_o}\right)_{fl.}$ = 4.97

L (cms.)	ΔH (cms.water)	u_m (ft./sec.)	Re_m	$K_{\Delta H}$	ψ'	ψ	ϵ (per cent.)	$f(\epsilon)$
40.0	0.0	0.0	-	-	-	-	50.0	-
40.0	15.0	0.00584	0.744	284	44.9	1369	50.0	0.02702
40.0	26.8	0.01023	1.304	508	26.1	797	50.0	0.02762
40.0	50.9	0.01944	2.475	965	13.7	421	50.5	0.02996
40.4	43.6	0.0174	2.216	826	15.6	449	50.5	0.03074
40.4	51.1	0.02034	2.591	968	13.4	385	50.5	0.03118
40.6	61.5	0.02348	2.991	1165	12.4	348	50.7	0.03078
40.7	69.1	0.02528	3.220	1309	12.5	337	50.9	0.02968
40.5	74.1	0.02978	3.793	1404	9.2	261	50.6	0.03342
41.3	79.0	0.03257	4.150	1496	9.2	232	51.6	0.03490
41.8	84.3	0.03595	4.580	1597	8.6	203	52.2	0.03696
42.2	89.1	0.0391	4.980	1688	8.1	182	52.6	0.03858
42.2	94.7	0.041	5.220	1794	7.8	176	52.6	0.03818
44.5	91.3	0.0499	6.360	1730	6.7	114	55.1	0.05090

TABLE LXIX (Continued)

L (cms.)	ΔH (cms. water)	u_m (ft./sec.)	Re_m	$K_{\Delta H}$	ψ'	ψ	ϵ (per cent.)	$f(\epsilon)$
46.0	90.6	0.0569	7.250	1716	5.9	87.0	56.5	0.06034
47.5	90.8	0.0655	8.350	1720	5.2	66.0	57.9	0.072
49.5	92.5	0.0712	9.070	1752	5.4	57.0	59.6	0.0781

TABLE LXX - Medium Galena

$D_p = 0.0174$ in.; $\mu = 0.000728$ lbs./ft.sec.; $L_o = 23.3$ cms.;

$\rho s = 6.47$ g./ml.; $\rho f = 0.999$ g./ml.; $(\frac{\Delta H}{L_o})_{fl.} = 5.07$

L (cms.)	ΔH (cms.water)	u_m (ft./sec.)	Re_m	$K_{\Delta H}$	ψ'	ψ	ϵ (per cent.)	$f(\epsilon)$
46.8	0.0	0.0	-	-	-	-	50.2	-
46.8	11.9	0.00438	0.544	184	55.6	1659	50.2	0.02984
46.8	18.4	0.00641	0.796	285	40.1	1198	50.2	0.02906
46.8	34.1	0.01157	1.437	528	22.9	682	50.2	0.0298
46.9	49.3	0.0163	2.025	763	16.8	496	50.3	0.02984
47.0	62.8	0.02016	2.554	972	13.7	398	50.4	0.03070
47.0	44.2	0.01471	1.828	684	18.8	546	50.4	0.03006
47.1	53.6	0.01787	2.220	829	15.8	454	50.5	0.03044
46.1	64.9	0.02112	2.623	1004	12.7	389	50.0	0.03056
46.9	73.3	0.02438	3.028	1134	11.2	330	50.3	0.03152
48.0	83.8	0.02988	3.710	1297	9.9	252	51.5	0.0350
48.3	92.3	0.0336	4.173	1428	8.9	219	51.8	0.0370
49.6	105.9	0.0407	5.040	1638	8.0	171	53.0	0.04078

TABLE LXX (Continued)

L (cms.)	ΔH (cms.water)	u_m (ft./sec.)	Re_m	$K_{\Delta H}$	ψ'	ψ	ϵ (per cent.)	f (ϵ)
50.0	107.5	0.04685	5.820	1662	6.4	131	53.4	0.0470
53.3	109.7	0.0547	6.800	1696	6.5	98.0	56.3	0.05616
55.2	108.6	0.0604	7.510	1679	6.2	79.5	57.8	0.06478
57.7	108.0	0.0702	8.720	1670	5.5	58.5	59.6	0.07864

TABLE LXXI - Coarse Galena

D_p = 0.028 in.; μ = 0.000767 lbs./ft.sec.; L_o = 5.2 cms.;

ρs = 6.4 g./ml.; ρf = 0.999 g./ml.; $(\frac{\Delta H}{L_o})_{fl.}$ = 5.2

L (cms.)	ΔH (cms.water)	u_m (ft./sec.)	Re_m	$K_{\Delta H}$	ψ'	ψ	ϵ (per cent.)	$f(\epsilon)$
11.2	0.0	0.0	-	-	-	-	53.6	-
11.2	5.2	0.01482	2.808	1354	22.8	459	53.6	0.02444
11.2	9.7	0.0272	5.120	2525	12.8	257	53.6	0.02686
11.2	13.7	0.0379	7.180	3567	4.3	185	53.6	0.02874
11.4	19.6	0.0541	11.390	5100	5.7	105	54.4	0.0362
11.4	21.9	0.0606	12.770	5700	5.4	98.5	54.4	0.03798
11.4	22.8	0.0628	13.230	5936	4.9	90.5	54.4	0.03812
11.4	24.7	0.0682	14.350	6430	4.6	83.5	54.4	0.03928
11.3	24.4	0.0675	14.210	6350	4.1	84.0	54.0	0.03928
11.4	25.8	0.0712	15.000	6720	4.1	79.5	54.4	0.0400
11.7	28.3	0.0781	16.450	7870	4.8	78.0	55.5	0.03872
12.0	30.4	0.838	17.650	7920	4.7	68.0	56.7	0.04222

TABLE LXXII - Coarse Galena

D_p = 0.028 in.; μ = 0.000728 lbs./ft.sec. L_o = 10.9 cms.;

ρ_s = 6.4 g./ml.; ρ_f = 0.999 g./ml.; $(\frac{\Delta H}{L_o})_{fl.}$ = 4.88

L (cms.)	ΔH (cms.water)	u_m (ft./sec.)	Re_m	$K_{\Delta H}$	ψ'	ψ	ϵ (per cent.)	f(ϵ)
21.8	0.0	0.0	-	-	-	-	50.0	-
21.8	6.5	0.01258	2.510	895	12.4	379	50.0	0.03246
21.8	13.9	0.02325	4.690	1914	7.7	233	50.0	0.0314
21.8	19.4	0.03054	6.090	2670	6.3	192	50.0	0.03126
21.8	24.2	0.0366	7.320	3332	5.5	166	50.0	0.03164
21.8	30.1	0.0437	8.730	4142	4.8	145	50.0	0.03158
21.8	34.6	0.0492	9.830	4762	4.3	132	50.0	0.03202
22.0	41.1	0.0575	11.480	5660	4.0	115	50.5	0.0332
22.0	44.6	0.0621	12.390	6140	3.7	107	50.5	0.03364
22.3	44.8	0.0623	12.450	6170	4.0	106	51.2	0.03396
22.3	49.2	0.0684	13.670	6772	3.7	97.0	51.2	0.03476
22.3	48.2	0.0672	13.440	6636	3.7	98.0	51.2	0.03470
22.3	52.5	0.0732	14.640	7230	3.4	90.0	51.2	0.03590
22.3	52.1	0.0733	14.650	7242	3.4	90.0	51.2	0.0358

TABLE LXXII (Continued)

L (cms.)	ΔH (cms. water)	u_m (ft./sec.)	Re_m	$K_{\Delta H}$	ψ'	ψ	ϵ (per cent.)	$f(\epsilon)$
23.2	50.9	0.0823	16.450	7010	3.3	69.0	53.1	0.04350
23.7	50.3	0.0854	17.070	6922	3.3	63.5	54.1	0.046
23.8	49.8	0.0936	18.720	6895	2.8	52.5	54.2	0.0524

TABLE LXXIII - Coarse Galena

D_p = 0.028 in.; μ = 0.00071 lbs./ft.sec.; L_o = 13.5 cms.;
ρ_s = 6.4 g./ml.; ρ_f = 0.999 g./ml.; $(\frac{\Delta H}{L})_{fl.}$ = 4.83

L (cms.)	ΔH (cms.water)	u_m (ft./sec.)	Re_m	$K_{\Delta H}$	ψ'	ψ	ϵ (per cent.)	$f(\epsilon)$
27.0	0.0	0.0	-	-	-	-	50.0	-
27.0	8.3	0.01135	2.327	971	15.7	478	50.0	0.02758
27.0	15.6	0.02033	4.170	1824	9.2	280	50.0	0.02876
27.0	21.1	0.02674	5.480	2466	7.2	219	50.0	0.02974
27.0	27.0	0.03315	6.790	3156	6.0	183	50.0	0.03026
27.1	29.2	0.0355	7.270	3415	5.7	173	50.2	0.03044
27.1	31.5	0.03785	7.760	3682	5.4	163	50.0	0.03068
27.1	37.1	0.04348	8.910	4338	4.9	146	50.2	0.03118
27.1	41.1	0.04762	9.760	4802	4.5	135	50.2	0.03160
27.2	48.2	0.0544	11.150	5637	4.2	121	50.4	0.03208
27.2	53.1	0.05897	12.080	6210	3.9	114	50.4	0.03228
27.3	59.0	0.0647	13.260	6900	3.7	105	50.6	0.03304
27.5	63.2	0.0691	14.170	7390	3.6	98.0	50.9	0.03368
27.8	64.2	0.07595	15.570	7505	3.2	82.5	51.4	0.03760
29.0	61.8	0.0837	17.15	7230	3.2	65.5	55.3	0.04430

TABLE LXXIV - Coarse Galena

$D_p = 0.028$ in.; $\mu = 0.000728$ lbs./ft.sec.; $L_o = 18.5$ cms.;

$\rho_s = 6.4$ g./ml.; $\rho_f = 0.999$ g./ml.; $\left(\frac{\Delta H}{L_o}\right)_{fl.} = 4.97$

L (cms.)	ΔH (cms.water)	u_m (ft./sec.)	Re_m	$K_{\Delta H}$	ψ'	ψ	ϵ (per cent.)	$f(\epsilon)$
37.0	0.0	0.0	-	-	-	-	50.0	-
37.0	9.9	0.00955	1.906	803	19.4	590	50.0	0.02646
37.0	15.8	0.01483	2.960	1282	12.5	380	50.0	0.02742
37.1	25.6	0.02314	4.620	2078	8.6	260	50.1	0.02848
37.1	25.4	0.02853	5.690	2061	5.6	170	50.1	0.03708
37.1	32.3	0.03355	6.650	2621	5.2	158	50.1	0.03546
37.1	38.8	0.03895	7.770	3150	4.6	139	50.1	0.03600
37.1	46.6	0.0418	8.340	3782	4.8	145	50.1	0.03276
37.1	50.8	0.0482	9.620	4122	3.9	119	50.1	0.03572
37.1	60.4	0.0512	10.220	4901	4.2	126	50.1	0.03290
37.1	64.5	0.0560	11.170	5232	3.7	112	50.1	0.03446
36.8	70.6	0.0619	12.350	5730	3.2	101	49.7	0.03632
37.4	76.8	0.0618	12.330	6230	3.8	110	50.5	0.03306
38.0	76.7	0.0667	13.310	6225	3.6	94.0	51.3	0.03672

TABLE LXXIV (Continued)

L (cms.)	ΔH (cms.water)	u_m (ft./sec.)	Re_m	$K_{\Delta H}$	ψ'	ψ	ϵ (per cent.)	$f(\epsilon)$
38.0	81.2	0.0686	13.690	6590	3.6	94.0	51.3	0.03608
38.2	82.7	0.0703	14.03	6762	3.7	92.0	51.6	0.03588
38.2	85.5	0.0720	14.36	6940	3.5	89.5	51.6	0.03644
38.5	86.8	0.0739	14.75	7045	3.5	85.0	51.9	0.03790
38.7	87.9	0.0749	14.94	7135	3.6	85.5	52.2	0.03744
38.2	91.5	0.0829	16.54	7423	2.9	72.5	51.6	0.04110
39.5	89.8	0.0977	19.49	7287	2.4	51.0	53.2	0.05276

TABLE LXXV - Fine Coal

D_p = 0.0099 in.; μ = 0.000676 lbs./ft.sec.; L_o = 9.0 cms.;

ρ_s = 1.38 g./ml.; ρ_f = 0.998 g.ml.; $(\frac{\Delta H}{L})_{fl.}$ = 0.27

L (cms.)	Δ H (cms. water)	u_m (ft./sec.)	Re_m	$K_{\Delta H}$	ψ'	ψ	ϵ (per cent.)	f(ϵ)
17.5	0.0	0.0	-	-	-	-	48.6	-
17.5	1.6	0.000254	0.0193	13.9	823	99600	48.6	0.01285
17.5	2.2	0.000388	0.0295	18.2	462	55850	48.6	0.01486
19.9	2.6	0.000711	0.054	22.2	437	20305	54.8	0.02216
21.0	2.4	0.000987	0.075	20.5	294	9720	57.2	0.03292
22.0	2.4	0.001237	0.094	20.5	243	6190	59.1	0.0436
22.0	2.8	0.001487	0.113	23.9	196	4993	59.1	0.04408
22.5	2.6	0.001882	0.143	22.2	128.6	2895	60.0	0.0608
23.0	2.9	0.002488	0.189	24.8	93.6	1852	60.9	0.07292
24.0	2.9	0.003493	0.266	24.8	80.2	936	62.5	0.10374
27.0	2.6	0.00508	0.386	22.2	44.1	398	66.7	0.1736
35.2	2.4	0.00821	0.624	20.5	24.2	141	74.4	0.3098
49.5	2.4	0.01224	0.930	20.5	16.02	64.0	81.8	0.4770

TABLE LXXVI - Medium Coal

D_p = 0.0174 in.; μ = 0.000676 lbs./ft.sec.; L_o = 9.0 cms.;

ρs = 1.35 g./ml.; ρf = 0.998 g./ml.; $\left(\frac{\Delta H}{L_o}\right)_{fl.}$ = 0.33

L (cms.)	ΔH (cms. water)	u_m (ft./sec.)	Re_m	$K_{\Delta H}$	Ψ'	Ψ	$\in$ (per cent.)	$f(\in)$
17.2	0.0	0.0	-	-	-	-	48.0	-
17.3	2.2	0.001011	0.135	102	111.2	14935	48.0	0.01256
19.7	2.9	0.001572	0.210	134	162	8105	54.3	0.015050
20.4	3.0	0.00292	0.390	139	61.5	2438	55.9	0.02770
25.5	3.4	0.00966	1.290	158	24.75	253	64.7	0.08910
28.9	3.2	0.01292	1.725	148	18.28	133	68.8	0.1286
35.0	3.1	0.0164	2.190	144	13.66	80.0	74.3	0.1750
41.7	2.8	0.01954	2.610	129	10.8	51.0	78.4	0.2334
50.0	2.9	0.0227	3.030	135	9.63	39.0	82.0	0.2666
58.0	3.1	0.0256	3.420	144	9.41	33.0	84.5	0.288
71.5	2.6	0.0312	4.170	121	6.05	18.5	87.4	0.4324

TABLE LXXVII - Coarse Coal

$D_p = 0.028$ in.; $\mu = 0.000767$ lbs./ft.sec.; $L_o = 8.8$ cms.;

$\rho s = 1.38$ g./ml.; $\rho f = 0.999$ g./ml.; $(\frac{\Delta H}{L_o})_{fl.} = 0.42$

L (cms.)	ΔH (cms.water)	u_m (ft./sec.)	Re_m	$K_{\Delta H}$	ψ'	ψ	ϵ (per cent.)	$f(\epsilon)$
17.5	0.0	0.0	-	-	-	-	49.8	-
17.5	1.2	0.001325	0.2514	185	78.2	7790	49.8	0.01310
17.7	2.4	0.00281	0.533	369	37.5	3463	50.3	0.01458
17.9	3.0	0.00363	0.689	461	30.4	2590	50.8	0.01544
19.4	3.1	0.00457	0.867	477	35.9	1694	54.7	0.01902
19.4	3.6	0.00422	0.801	553	48.7	2298	54.7	0.01502
22.8	3.5	0.01134	2.150	538	16.6	310	61.4	0.04572
23.6	3.8	0.01404	2.660	584	13.96	220	62.7	0.05364
26.5	3.4	0.0202	3.830	522	10.63	95.0	66.8	0.0916
30.5	3.6	0.0263	4.970	554	8.61	60.0	71.2	0.1166
37.6	3.7	0.0352	6.680	569	6.56	34.0	76.6	0.1632
45.4	3.9	0.0428	8.120	600	5.78	24.5	80.6	0.1964
56.7	3.8	0.0515	9.770	584	4.71	16.5	84.5	0.2576
71.5	4.5	0.0582	11.040	692	4.97	15.0	87.7	0.2588

ANALYTICAL TREATMENT (1)

Graphed Data

Figures 29,30 and 31 show the relationship between the friction factor ψ and the Reynolds Number for sand, galena and coal.

A comparison of these graphs shows that:-

(a) with all the materials the graphs are of the same form and follow a like course.

(b) in each case, the graphs can be divided into:-

- (i) a portion representative of consolidated and expanded conditions
- (ii) portions representative of teetering conditions, one for each size of material examined, these being parallel to one another.

(c) the junctions of the portions referred to in (b) (i) and (ii) above, represent the conditions at which the fluidization occurs, that is to say, they are the fluidization points.

These points are of course the same as those shown as break or fluidization points in Figures 17 - 19 and 22 - 27.

Theoretical Considerations

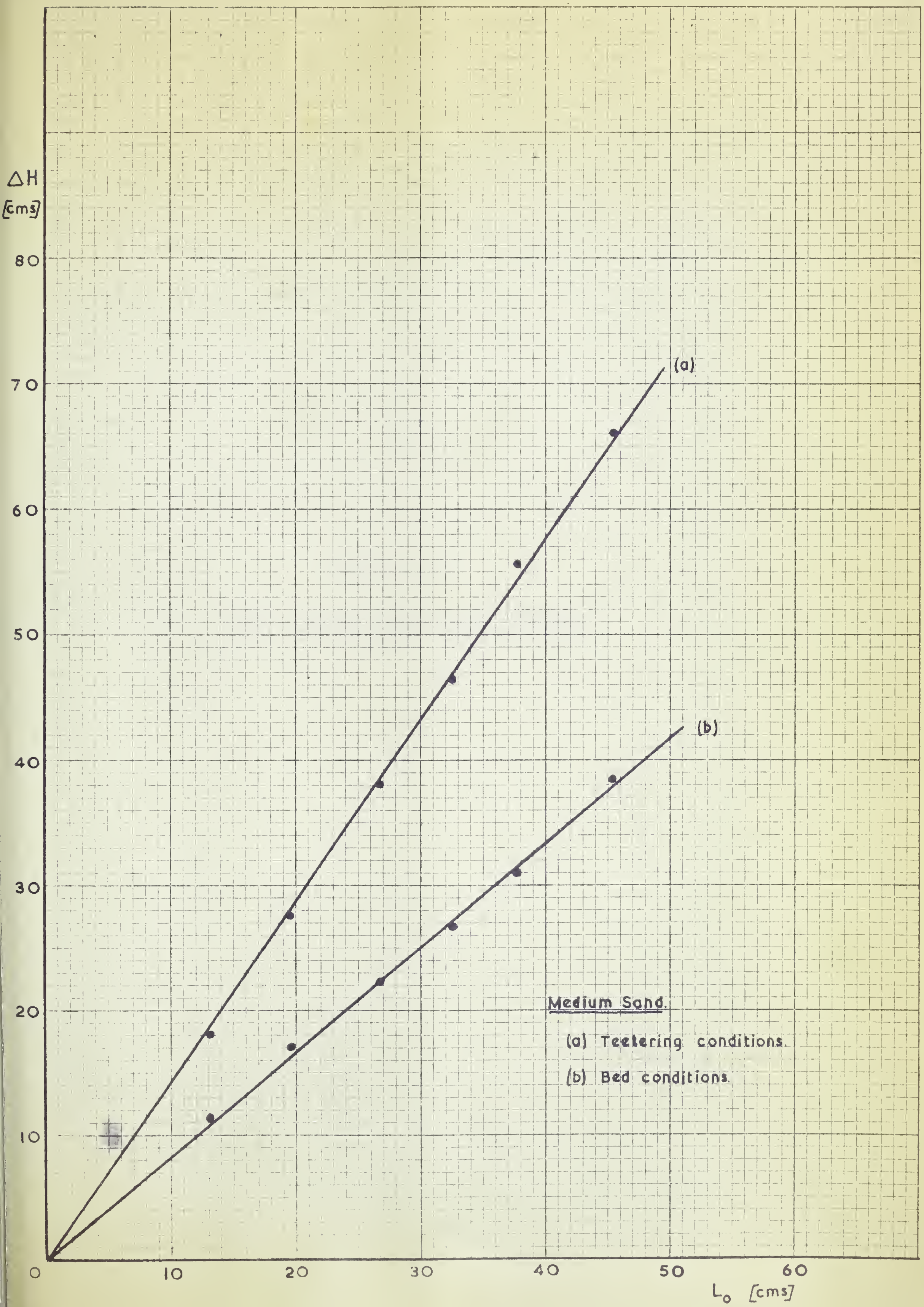
After fluidization occurs, the pressure drop remains substantially constant, although the rate of fluid flow is continually increasing.

The relationship of the maximum pressure drop reached, to the reduced depth of the bed, L_o, i.e. to a property directly proportional to the total weight of the bed, is shown in Figure 28.

The pressure drop through a teetering bed is caused by the friction between the particles and the fluid in the system. The total

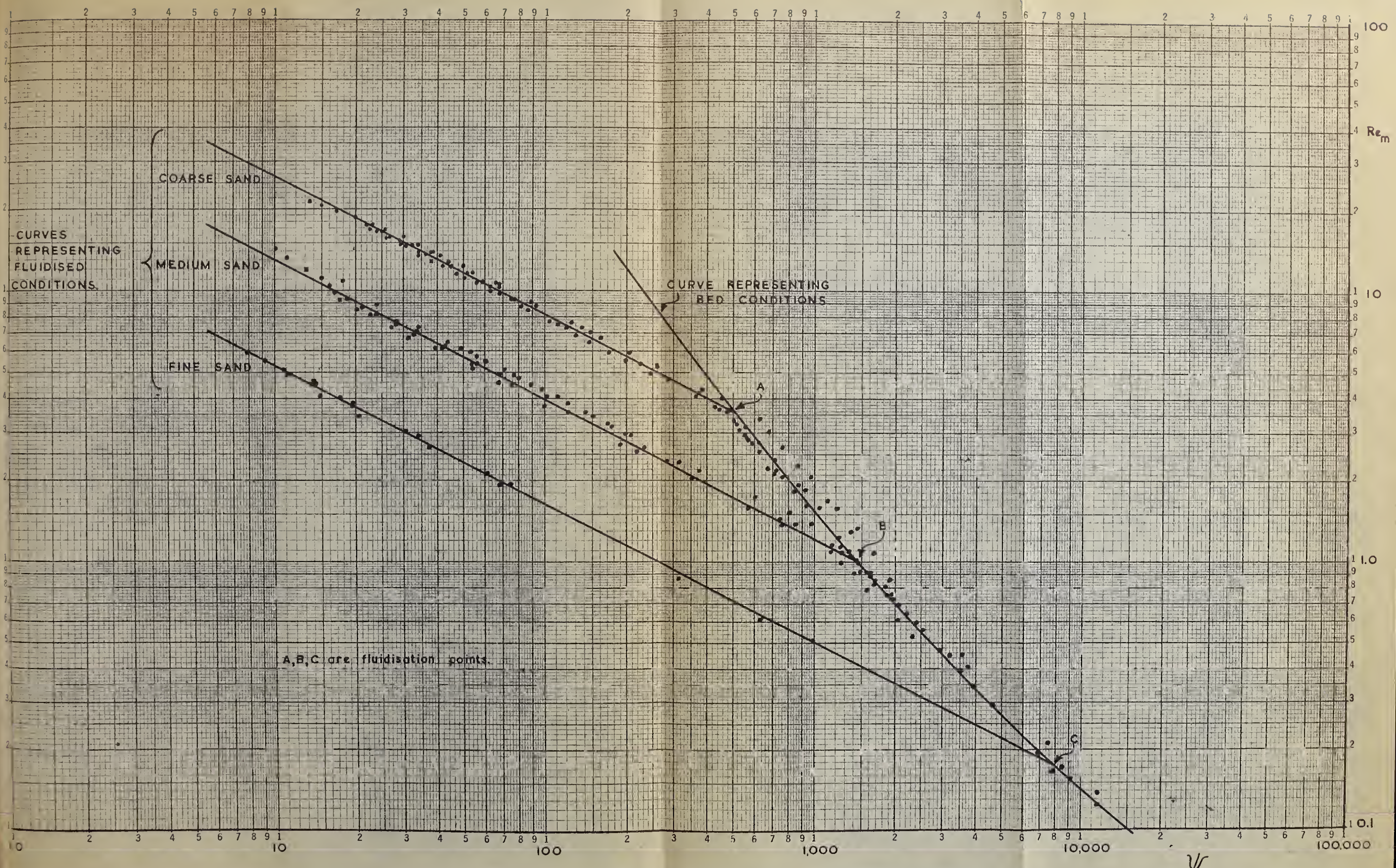
(Figure 28)

GRAPH SHOWING RELATIONSHIP BETWEEN THE MAXIMUM PRESSURE DROP AND THE REDUCED DEPTH OF BED FOR MEDIUM SAND.


ΔH [cms]
80
70
60
50
40
30
20
10
0
10
20
30
40
50
60
L_o [cms]
(a)
(b)
Medium Sand.
(a) Teetering conditions.
(b) Bed conditions.

(Figure 29)

GRAPH SHOWING RELATIONSHIP BETWEEN
ψ AND THE REYNOLDS NUMBER FOR SAND.

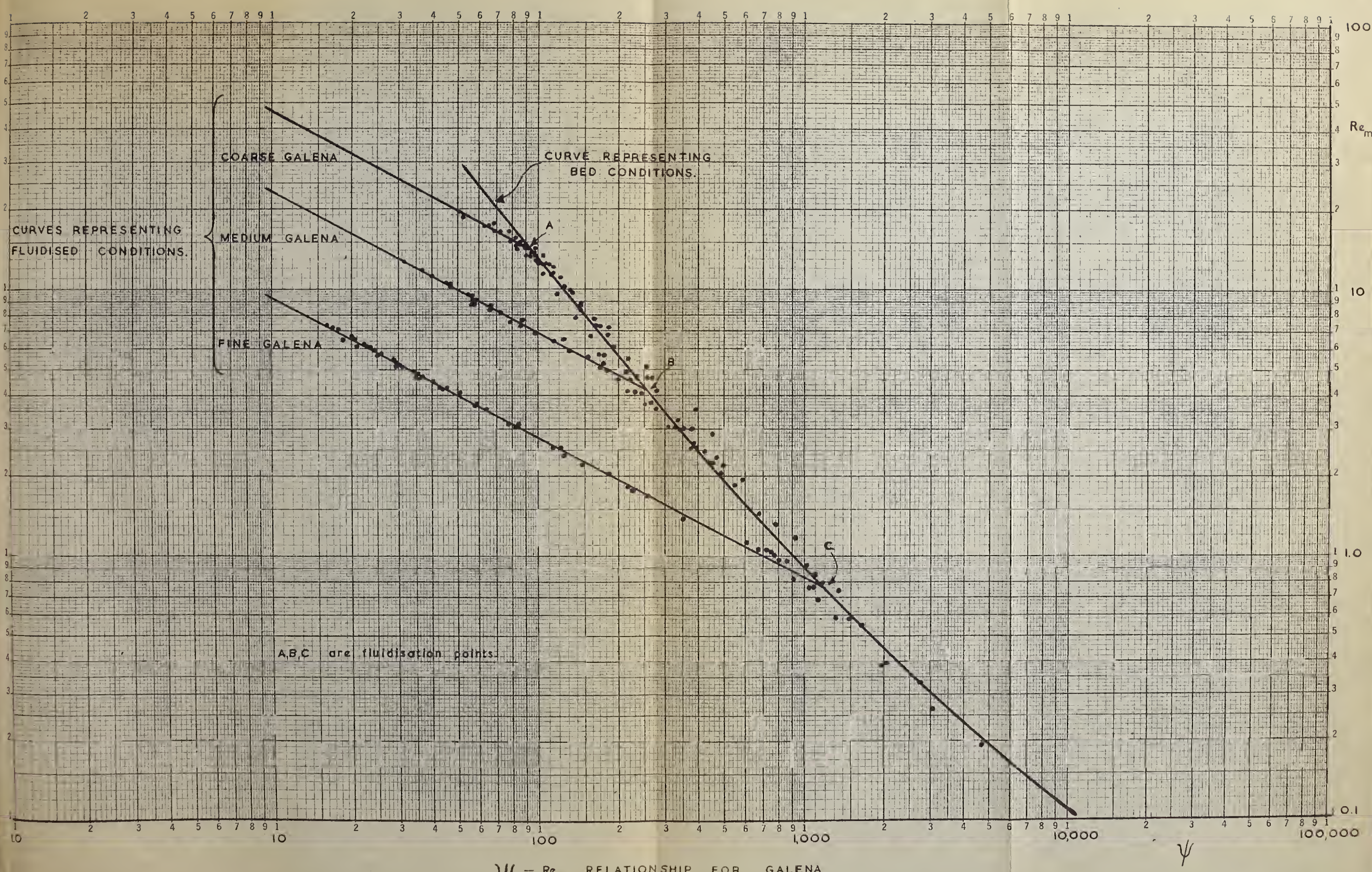


A,B,C are fluidisation points.

$\psi - Re_m$ RELATIONSHIP FOR SAND.

(Figure 30)

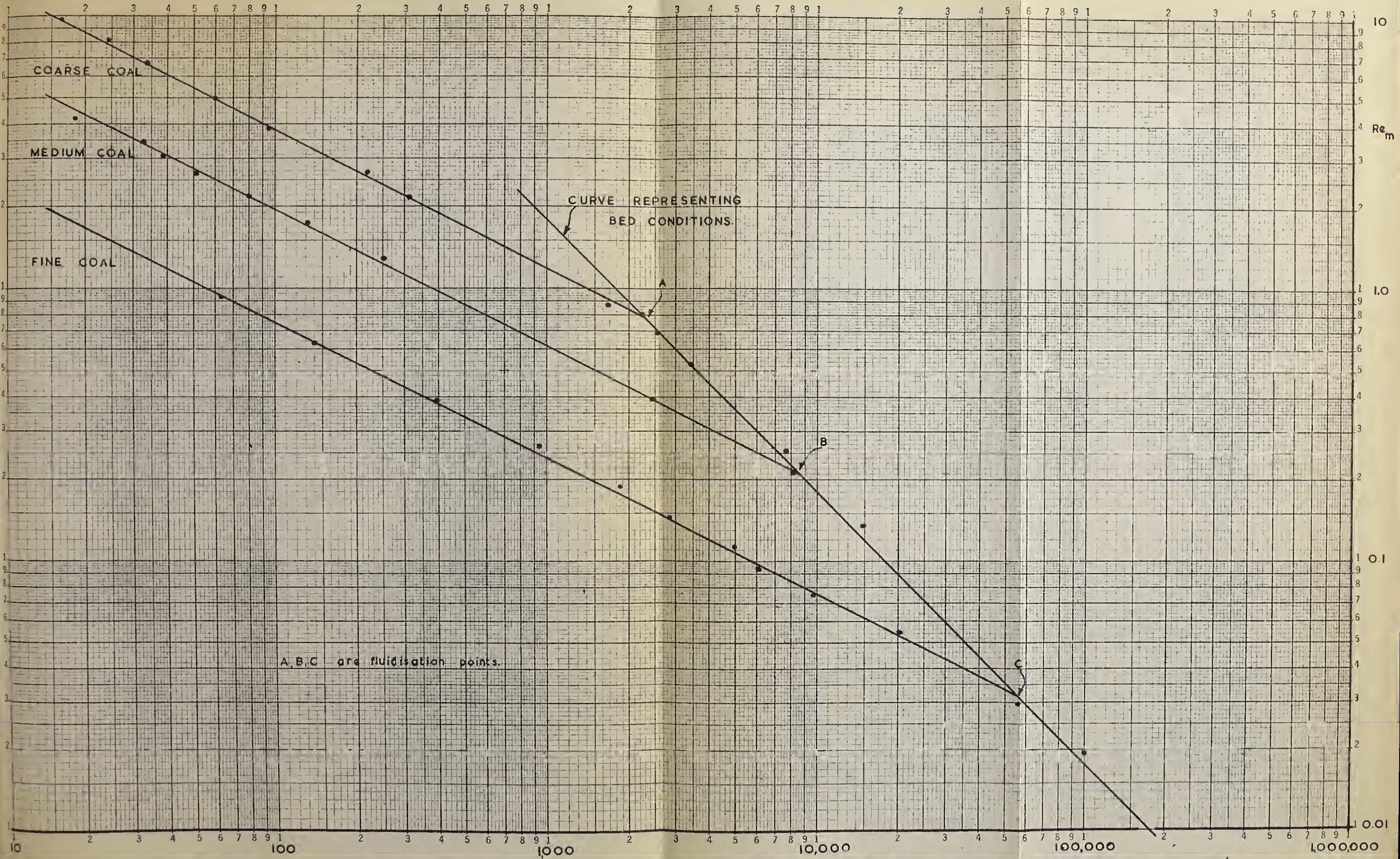
GRAPH SHOWING RELATIONSHIP BETWEEN ψ
AND THE REYNOLDS NUMBER FOR GALENA.



ψ — Re$_m$ RELATIONSHIP FOR GALENA

(Figure 31)

GRAPH SHOWING RELATIONSHIP BETWEEN ψ AND THE REYNOLDS NUMBER FOR COAL.



ψ — Re$_m$ RELATIONSHIP FOR COAL

pressure drop through the bed must therefore equal the sum of the frictional forces on all the particles constituting the bed.

In any system consisting of a single particle or a number of particles and a fluid medium, in which there is relative movement between the particles and the fluid; there are, in general, three forces acting on a particle.

They are:-

(1) the gravitational force, G, acting downwards

$$G = mg$$

(2) the buoyancy force, B, acting upwards

$$B = \frac{\pi}{6} D_p^3 \rho_f . g.$$

(3) the viscous drag or frictional force, F, acting in the direction in which the fluid is flowing.

A particle in an upward-flowing stream of fluid will move upwards or downwards (with respect to the container) according as (F + B) is greater than or less than G.

If (F + B) is equal to G the system is in equilibrium and the particle will neither move upwards nor downwards i.e. it is in the teeter condition.

For this condition:-

$$F = G - B$$

$$= mg - \frac{\pi}{6} D_p^3 \rho_f \cdot g.$$

$$= \frac{\pi}{6} D_p^3 \rho_s g - \frac{\pi}{6} D_p^3 \rho_f \cdot g$$

$$= g\frac{\pi}{6} D_p^3 (\rho_s - \rho_f) \qquad \text{- - - - - (3)}$$

For a bed consisting of a large number of particles

$$\Delta P.A = N. \frac{g \pi D_p^3}{6} (\rho_s - \rho_f) \qquad ----- (4)$$

Where A = cross-sectional area of the bed

N = the number of particles in the bed

ΔP = the pressure drop through the bed

The total volume of the particles themselves

$$N. \frac{\pi D_p^3}{6} = L_o.A$$

Therefore $A = \frac{N}{L_o} . \frac{\pi D_p^3}{6}$

Substituting in (4) we have:-

$$\Delta P. \frac{N}{L_o} . \frac{\pi D_p^3}{6} = N. g \pi D_p^3 (\rho_s - \rho_f)$$

or $\frac{\Delta P}{L_o} = g (\rho_s - \rho_f)$

but $\Delta P = \Delta H. \rho_f. g$

$$\frac{\Delta H}{L_o} = \frac{(\rho_s - \rho_f)}{\rho_f} \qquad ----- (5)$$

Accordingly the friction factor, ψ, which has been written as

$\frac{4}{3} . \frac{D_p g}{U_m^2} . \frac{(\Delta H)}{(L_o)}$ for consolidated and expanded beds, after fluidization has set in, can also be expressed as $\frac{4}{3} \frac{D_p g}{U_m^2} . \frac{(\rho_s - \rho_f)}{\rho_f}$

This latter expression is of course the drag coefficient which is commonly used in studying the behaviour of single particles falling freely in an infinite fluid, that is, free settling.

The frictional drag force, F, is dependent on the relative velocity between the particles and the fluid. In the simple case of a single particle suspended in an upward current of fluid, i.e. the case for which F = G - B, the velocity which is important in determining the value of the viscous drag force, F, is the velocity in the open tube, U_m. However, in the corresponding case of a teetering bed of particles, that is, where hindered settling conditions exist, the significant velocity is not U_m but the interstitial velocity inside the bed.

For this case, whether the particles be in a teetering condition or in a consolidated bed through which the fluid is passing the interstitial velocity is related in some way to the fluid velocity in the open tube above the bed and to the free cross-sectional area, which in turn is dependent on the voidage.

Accordingly it may be expected that free settling and hindered settling can be correlated in a like manner provided that due regard is given to the voidage factor of the whole system.

Considering the foregoing experimental work, a correlation was therefore sought employing the group, ψ', where,

$$\psi' = \frac{4}{3} \frac{D_p g}{U_m^2} \cdot \frac{\Delta H}{L_o} \cdot f(\epsilon) \qquad \text{- - - - - (6)}$$

ϵ = fractional voidage

Since for teetering conditions

$$\frac{\Delta H}{L_o} = \frac{\rho_s - \rho_f}{\rho_f}$$

ψ' may also be written as

$$\psi' = \frac{4}{3} \frac{D_p g}{U_m^2} \cdot \frac{\rho_s - \rho_f}{\rho_f} \cdot f(\epsilon)$$

It is customary to correlate data obtained for free settlement by the use of the group $\frac{4}{3} \frac{D_p g}{U_m^2} \cdot \frac{(\rho_s - \rho_f)}{\rho_f}$ (8)

Under conditions of free settling, in which case $\epsilon = 1.0$, the former more general equation becomes identical with the latter provided that the function contains no constant term.

The most reliable data for the free settlement of particles is that which may be obtained by the use of Schiller and Nauman's empirical equation:-

$$\psi^* = \frac{24}{Re_m} (1 + 0.15 \, Re_m^{0.687})$$

ψ^* here must be understood to refer to the drag coefficient with respect to Schiller and Nauman's investigations.

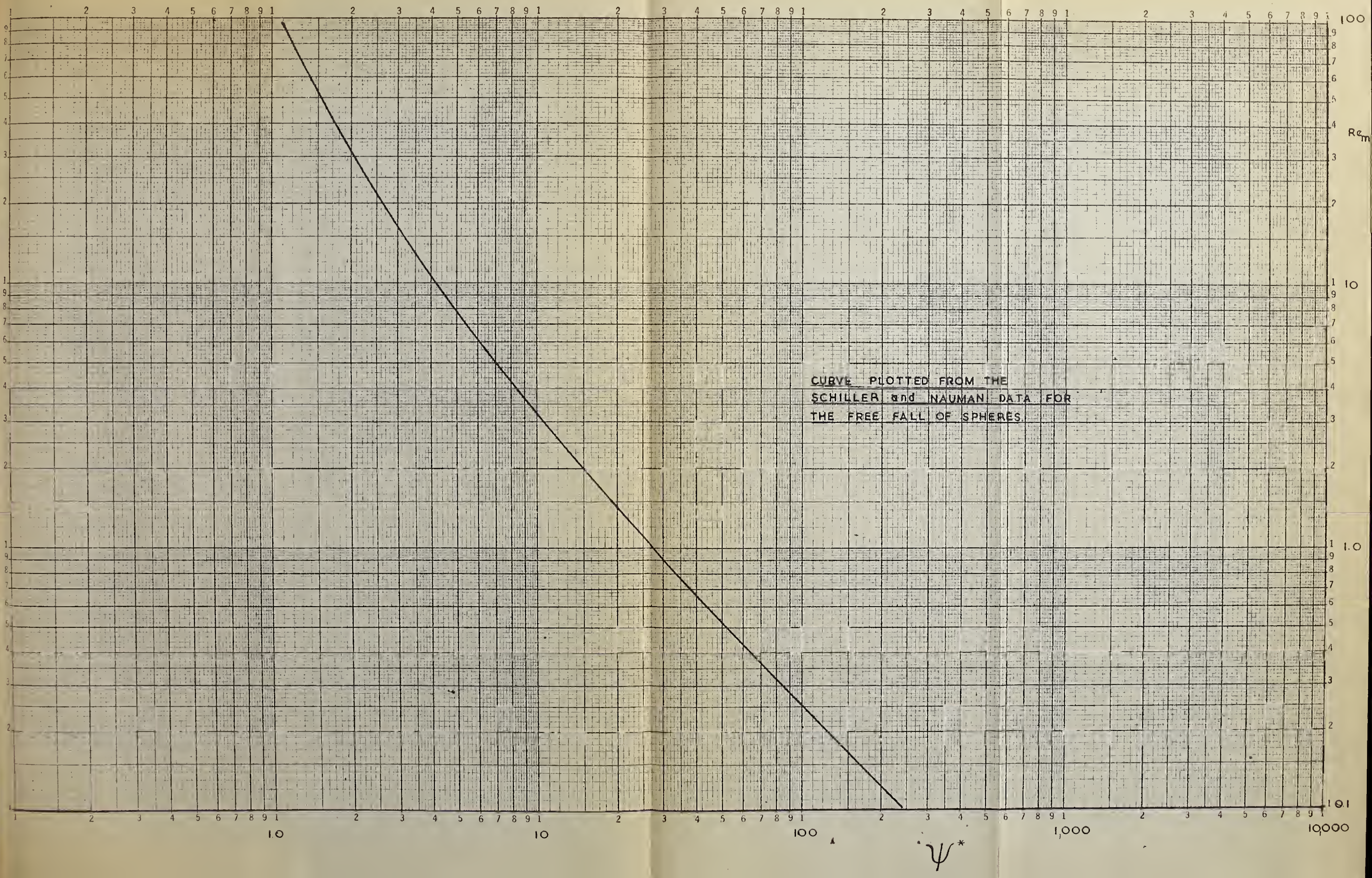
Schiller and Nauman's investigations were carried out using spherical particles. At this stage it is not proposed to deal with any differences which may be introduced by variations in particle shape or roughness.

A curve, based on Schiller and Nauman's data is given in Figure 32.

In order to determine the form of the voidage function, f (ϵ) for incorporation in the above group, ψ', the values for ψ and for ψ^* as shown by the Schiller and Nauman data for the appropriate Reynolds Numbers, have been compared.

(Figure 32)

GRAPH REPRESENTING THE SCHILLER AND NAUMAN DATA FOR THE FREE FALL OF SPHERES.



CURVE PLOTTED FROM THE SCHILLER and NAUMAN DATA FOR THE FREE FALL OF SPHERES.

The Schiller and Nauman values were taken from the preceding graph; the values for ψ were those experimentally determined and given in the foregoing tables. These two values were then expressed in the form of the ratio $\frac{\psi\text{(Schiller Nauman)}}{\psi\text{(experimental)}} = \frac{\psi^*}{\psi}$. This expresses numerically the value of f (ϵ) for each experimental determination.

These values are tabulated as f (ϵ) in Tables XLIX to LXXVII.

In Figures 33, 34 and 35, the values of f (ϵ) are shown plotted against the corresponding values for ϵ, for the three materials.

It will be observed that in all three cases the curves shown have a definite S-shape indicating that the form of the function is a complex one.[x] To express this curve mathematically involves the use of an expression of the type:-

$$y = a_0 + a_1x + a_2x^2 + a_3x^3 \dots\dots\dots a\,x^k \qquad ----- (7)$$

For the derivation of a sufficiently accurate equation for such a curve, a fairly large number of terms would have to be used. Not only would the amount of calculation required by excessive, but the value of the derived equation is probably doubtful.

R. T. Hancock(8), who has devoted considerable attention to the question of the voidage factor states that the equation for the drag coefficient, usually adopted for free settlement, can be made to apply in cases of hindered settling and mass dispersions, provided that the sixth power of the voidage is used.

Other authors have proposed the use of similar simple functions as a means of introducing the voidage.

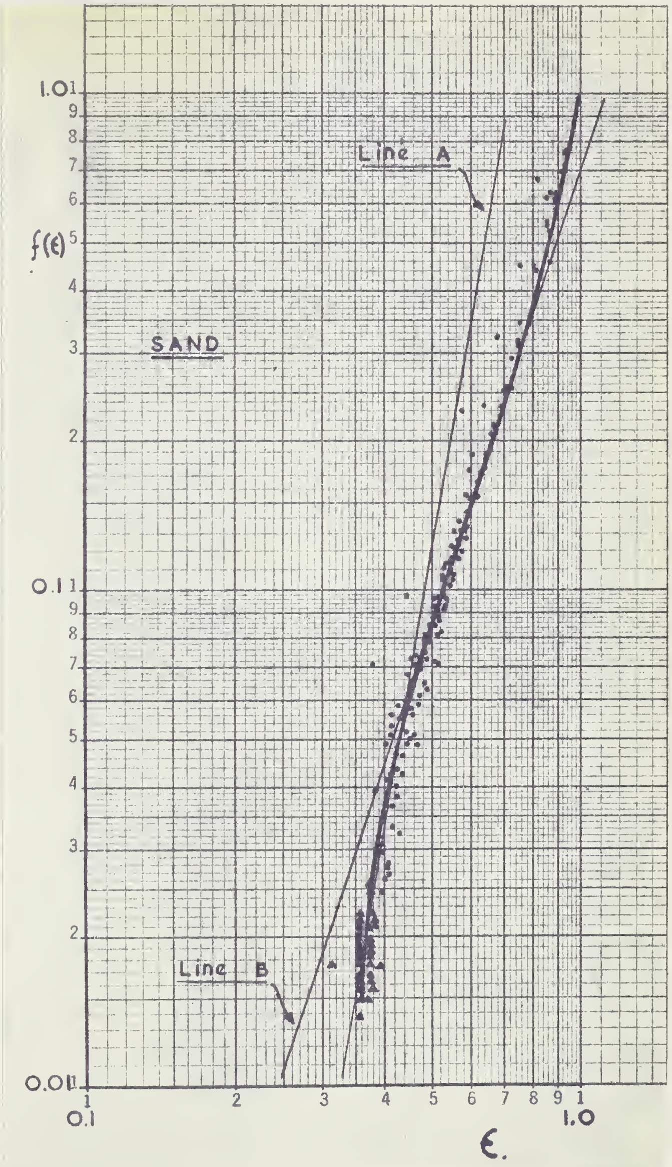
It is quite clear from the results of the investigations des-

---

[x] The examiners have pointed out to the author that the chief reason for the complexity of the function is probably due to the fact that the experimental data embrace viscous, transitional and turbulent regions.

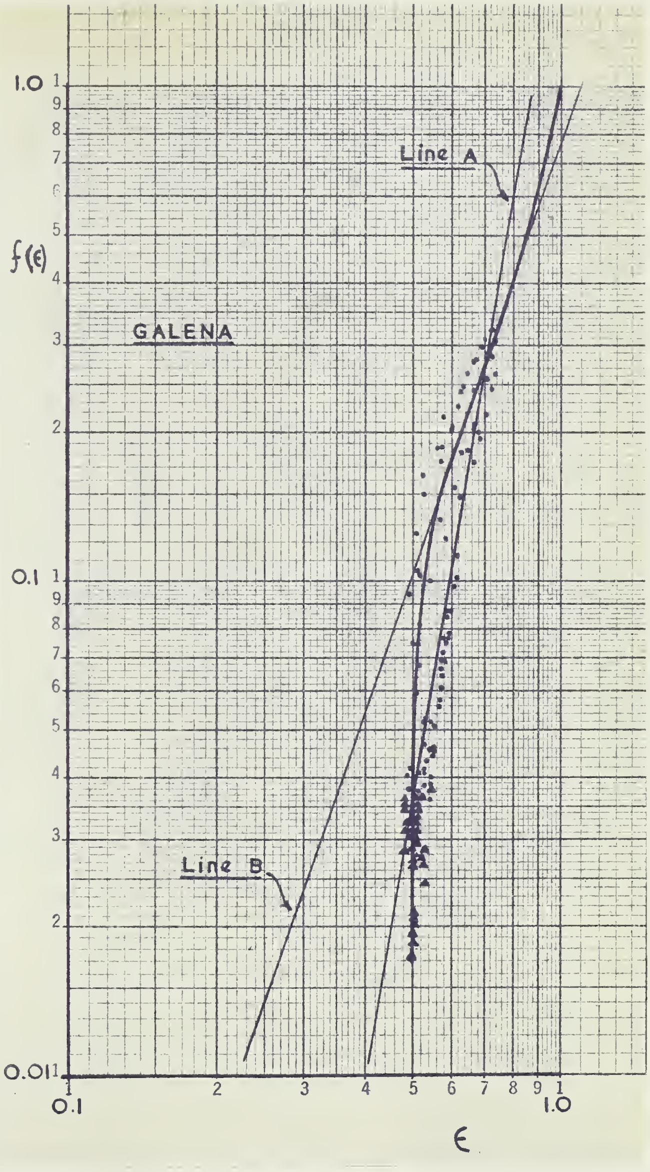
(Figure 33)

GRAPH SHOWING RELATIONSHIP BETWEEN THE VOIDAGE FUNCTION AND THE VOIDAGE FOR SAND.


1.0
0.1
0.01
f(ε)
SAND
Line A
Line B
1
2
3
4
5
6
7
8
9
0.1
1.0
ε.

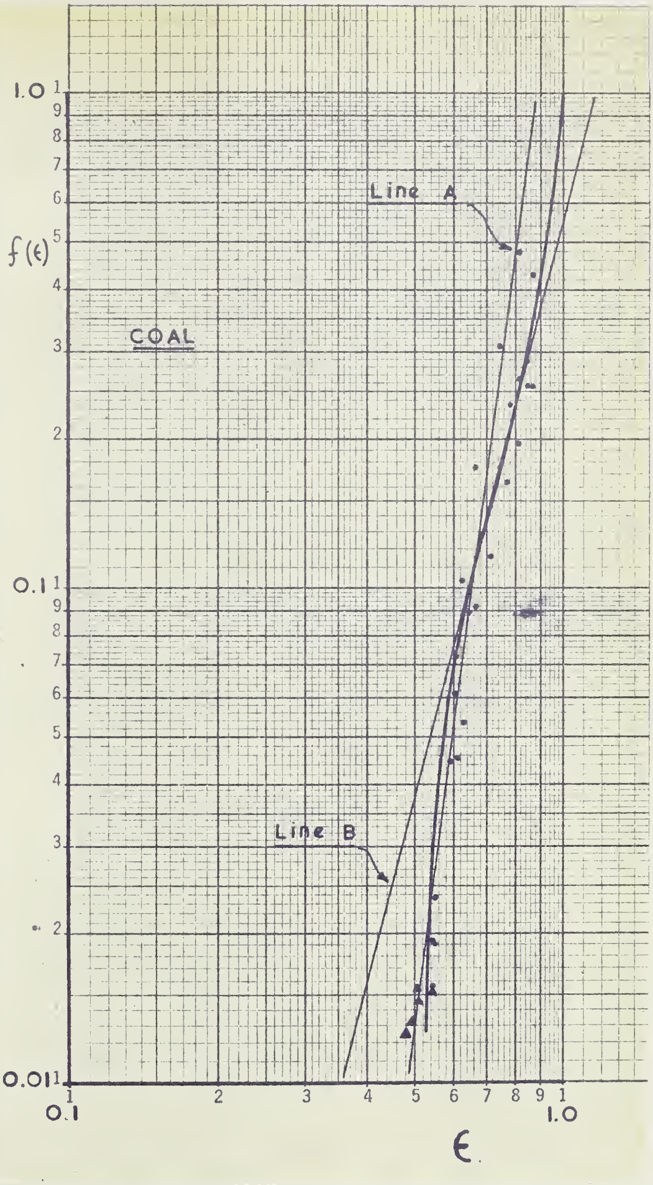
(Figure 34)

GRAPH SHOWING RELATIONSHIP BETWEEN THE VOIDAGE FUNCTION AND THE VOIDAGE FOR GALENA.


1.0
0.1
0.01
f(ϵ)
ϵ
0.1
1.0
1
2
3
4
5
6
7
8
9
GALENA
Line A
Line B

(Figure 35)

GRAPH SHOWING RELATIONSHIP BETWEEN THE VOIDAGE FUNCTION AND THE VOIDAGE FOR COAL.


1.0
f(ε)
COAL
Line A
Line B
0.1
0.01
0.1
1.0
ε
2
3
4
5
6
7
8
9

cribed in this thesis that no one simple function of the voidage is applicable. to viscous, transitional and turbulent conditions as encountered in this work.

Presumably, in previous work an insufficiency of numerical data led to the conception that some simple function of the voidage could be employed. (See however p.228.)

In so far that correct mathematical treatment of the curves shown in Figures 33 -35 is complex, it was decided to adopt a treatment involving approximation.

It will be clear that as far as the major part of the experimental data is concerned, each curve can be divided into two portions and that each portion may be fairly well represented by a straight line.

Since the curves are approximated as straight lines, the general form of the relationship is

$$f\,(\epsilon) = K.\,\epsilon^{n} \qquad \text{-----}\ (8)$$

Following this procedure, the values for K and n respectively for the three materials were determined and are given in Table LXXVIII.

In this table the constants and exponents are differentiated by subscripts A and B, which refer respectively to the lines A and B as shown in Figures 33 - 35.

In the case of every point shown on these graphs and listed in the preceding tables the appropriate K and n values to be used were determined by precise reference to the position of the point relative to the lines A and B.

TABLE LXXIX

Material	K_A	K_B	n_A	n_B
Sand	6.8	0.68	6	3
Galena	2.1	0.76	6	3
Coal	2.65	0.56	8	4

Using the values shown in Table LXXIX, the values for ψ' were computed from Equation (6) and are included in Tables XLIX - LXXVII.

The correlation of ψ' and Re_m is shown in Figures 36, 37 and 38 along with curves drawn from the Schiller and Nauman data for free-falling particles in an infinite fluid.

OBSERVATIONS

(1) Considering the graphs showing the comparison of the experimental results with the Schiller and Nauman data (Figures 36, 37 and 38), the spread of the points is only to be expected in view of the method of treatment adopted.

(2) Contrary to what might be anticipated, the exponent of the voidage for coal differs from that for sand and galena. No adequate explanation can be advanced for this occurrence at this stage. IT has been suggested That particle shape and roughness may be chiefly responsible for Th differen

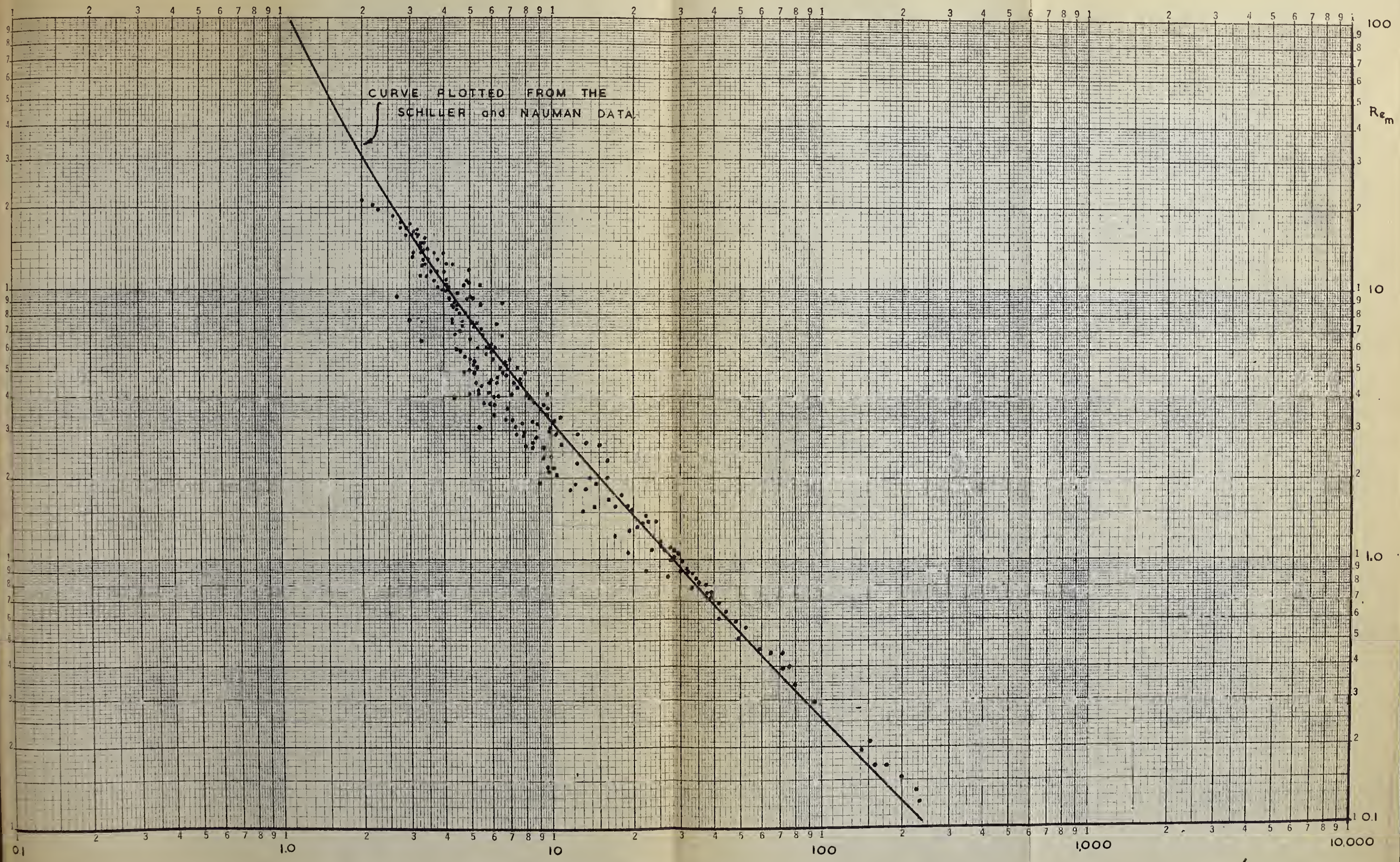
(3) Free settling grades regularly into hindered settling; the change is quite a smooth one and the differentiation which is indicated above is due to the method of treatment adopted.

(4) The modifications of the expression for the drag coefficient is to be interpreted as converting the fluid velocity, in the open tube, U_m, to a velocity representative of the interstitial velocity, U_i.

In the fluidization of a bed, it is obviously the interstitial

(Figure 36)

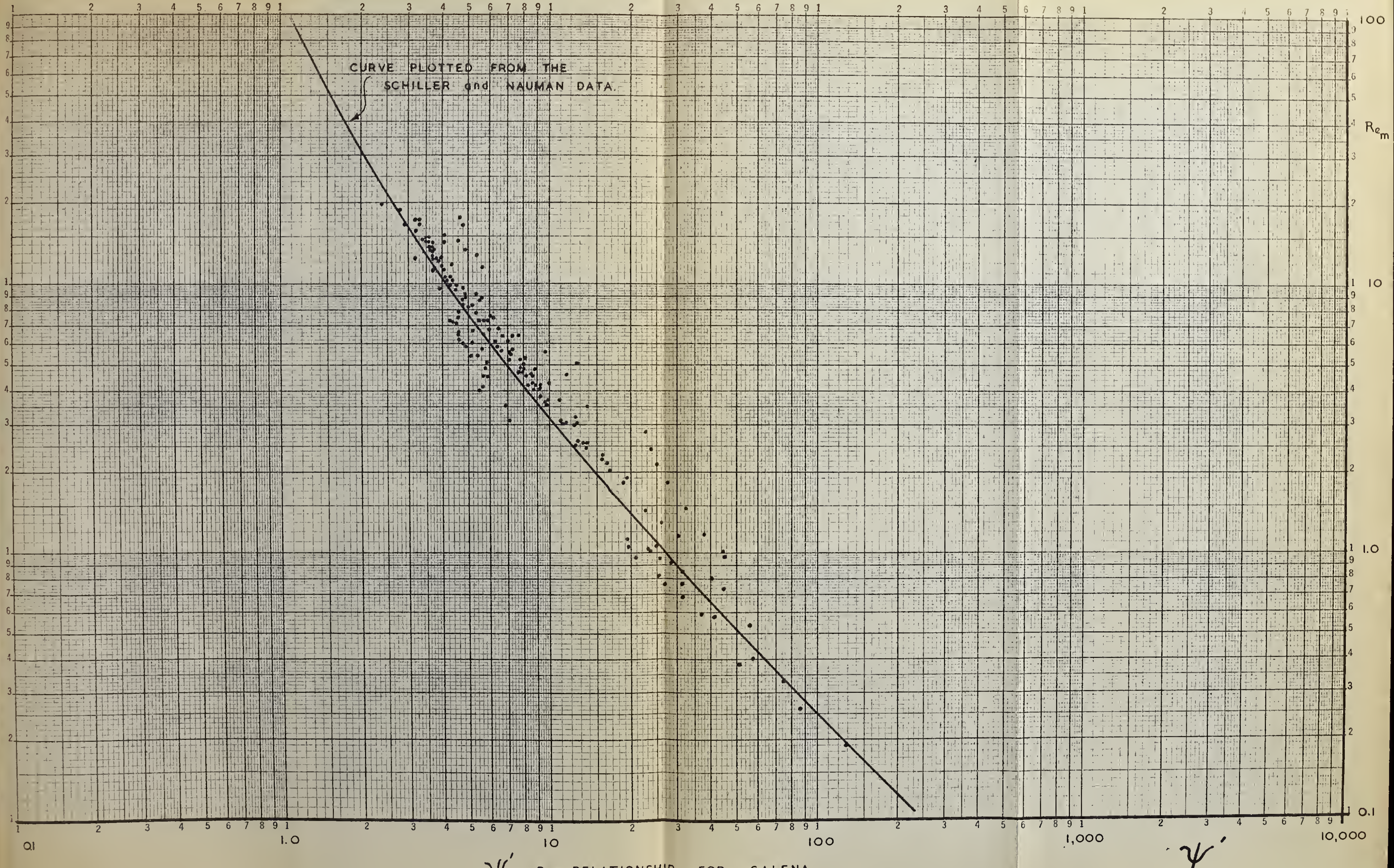
GRAPH SHOWING THE RELATIONSHIP BETWEEN ψ'
AND THE REYNOLDS NUMBER FOR SAND.



ψ' — Re_m RELATIONSHIP FOR SAND

(Figure 37)

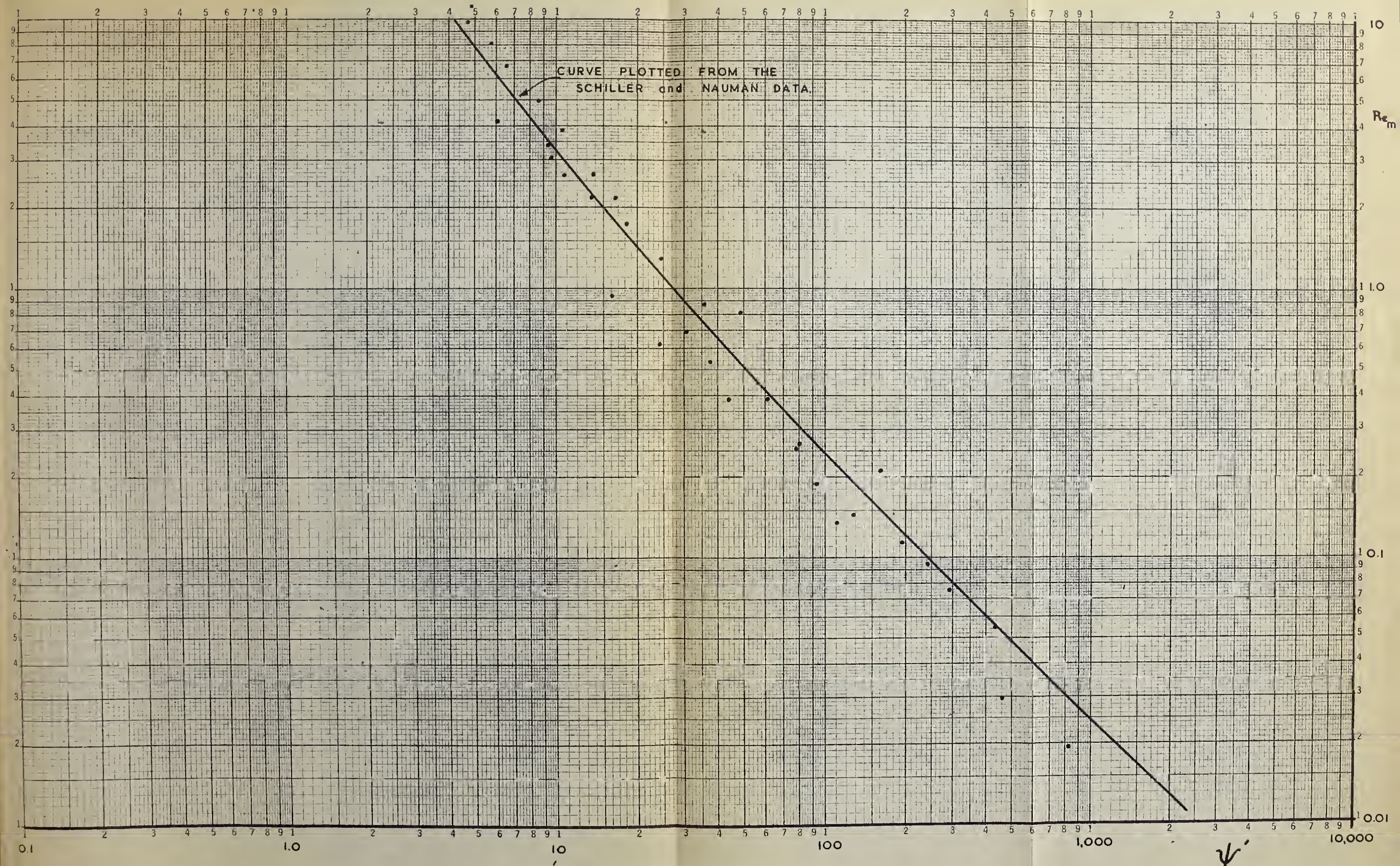
GRAPH SHOWING THE RELATIONSHIP BETWEEN ψ' AND THE REYNOLDS NUMBER FOR GALENA.



ψ' — Re_m RELATIONSHIP FOR GALENA

(Figure 38)

GRAPH SHOWING THE RELATIONSHIP BETWEEN ψ' AND THE REYNOLDS NUMBER FOR COAL.



ψ' – Re_m RELATIONSHIP FOR COAL

velocity and not the open tube velocity which is of importance.

Since it is not practicable to measure the interstitial velocity directly, the foregoing procedure permits the relationship between U_m and U_i to be expressed.

From elementary considerations, this relationship might be anticipated to be a simple one of the form:-

$$U_i = \frac{U_m}{\epsilon}$$

but further consideration makes it clear that under certain conditions not all of the voidage of the bed is involved in the flow of the fluid. Of necessity, there will be stagnant pockets of fluid held between the solid particles. Moreover, the "effective" voidage will not bear a constant relationship to the actual voidage, for the fraction which is effective will increase with the velocity of the fluid.

It is consequent upon this that the relationship is a complex one as shown by the above results.

Regarded in this way, the correct statement for all fluidised conditions is that $\psi = \frac{4}{3} \frac{D_p g}{U_i^2} \frac{(\rho_s - \rho_f)}{\rho_f}$ where U_i = interstitial velocity.

Under conditions of free settling, U_i is the same as U_m.

The above treatment has shown that for correlation one must write generally, that

$$\psi' = \frac{4}{3} \frac{D_p g}{U_m^2} \frac{(\rho_s - \rho_f)}{\rho_f} K.\epsilon^n \qquad ----- (9)$$

Comparing these two expressions

$$U_i^2 = \frac{U_m^2}{K\epsilon^n}$$

or $$U_i = U_m \times \frac{1}{\sqrt{K\epsilon^n}} \qquad ----- (10)$$

ANALYTICAL TREATMENT (2)

Some time after the experimental work described in this thesis was commenced, R. H. Wilhelm and M. Kwauk, published a paper entitled "Fluidization of Solid Particles"(9), in which apparatus and experiments were described, similar to those upon which the writer was engaged. The treatment adopted in the correlation of results by these authors differs from that described in Analytical Treatment (1).

It is considered desirable to treat the foregoing experimental data in the manner adopted by Wilhelm and Kwauk so that a comparison may be drawn with the results presented by these authors.

CORRELATION

The dimensionless groups chosen by these authors were

(a) $Re_o = \dfrac{D_p U_o \rho f}{\mu}$

(b) $\epsilon = \dfrac{L - L_o}{L}$

(c) $K_{\Delta P} = \dfrac{D_p^3 \rho f g}{2\mu^2} . \dfrac{\Delta P}{L_o}$

(d) $K_{\Delta\rho} = \dfrac{D_p^3 \rho f g (\rho s - \rho f)}{2\mu^2}$

For the most part, the symbols adopted for the variables are identical with those used in this thesis, except that the fluid velocity in the open tube has been designated by U_m and the Reynolds Number by Re_m.

$K_{\Delta p}$ is related to ψ in the following way:-

$$K_{\Delta p} = 3/8.\psi.Re_m^2 \qquad ----- (11)$$

The relationship of $K_{\Delta p}$ and $K_{\Delta \rho}$ will be understood from the discussion of the theoretical considerations on (p.191).

Wilhelm and Kwauk plotted $K_{\Delta p}$ v. Re_m to express generally pressure drop - velocity relationships.

The voidage factor ~~to~~ ϵ was purposely excluded from this graph.

This correlation appears to have been adopted primarily for design purposes since it provides a means for estimating pressure drops and fluidizing points.

For comparison purposes, the experimental data contained in this thesis has been recalculated on the basis used by Wilhelm and Kwauk, using the expression:-

$$K_{\Delta H} = \frac{1}{2} \cdot \frac{D_p^3.\rho f^2.g}{\mu^2} . \frac{\Delta H}{L_o}$$

The values of $K_{\Delta H}$ obtained are given in Table XLIX to LXXVII, and graphs of $K_{\Delta H}$ v. Re_m are shown in Figures 39, 40 and 41 which correspond to the above plot of Wilhelm and Kwauk. (Figure 13. loc. cit.).

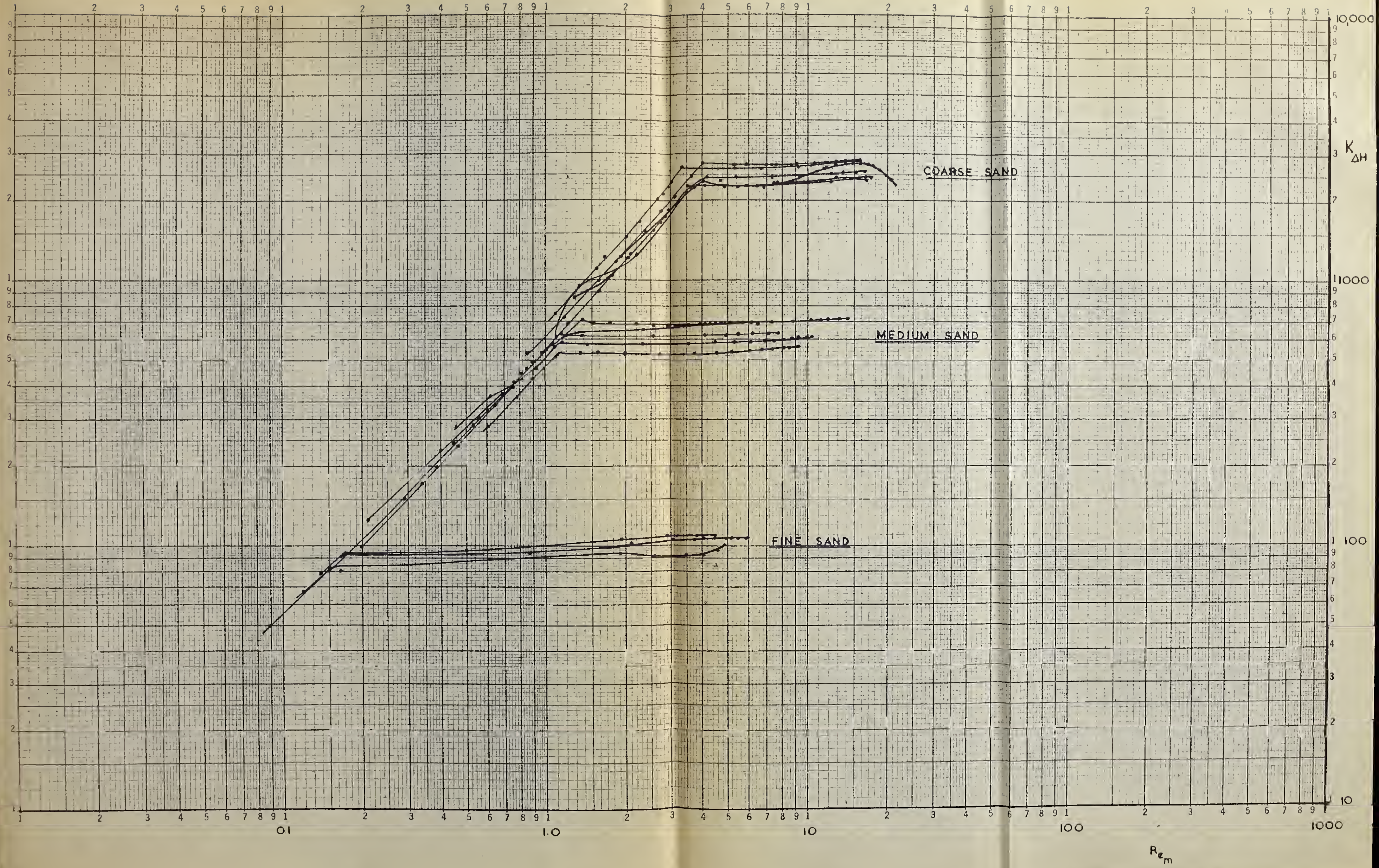
Comparison of the graphs shows that they are all of the same type. It should be noted that the published graph includes data obtained using air as the fluid as well as water.

Whereas in the published graph only one curve is given for a single size of a particular material, in Figures 39, 40 and 41 the degree of agreement between runs made using different amounts of bed material, is shown.

The range of Reynolds numbers covered by Wilhelm and Kwauk's

(Figure 39)

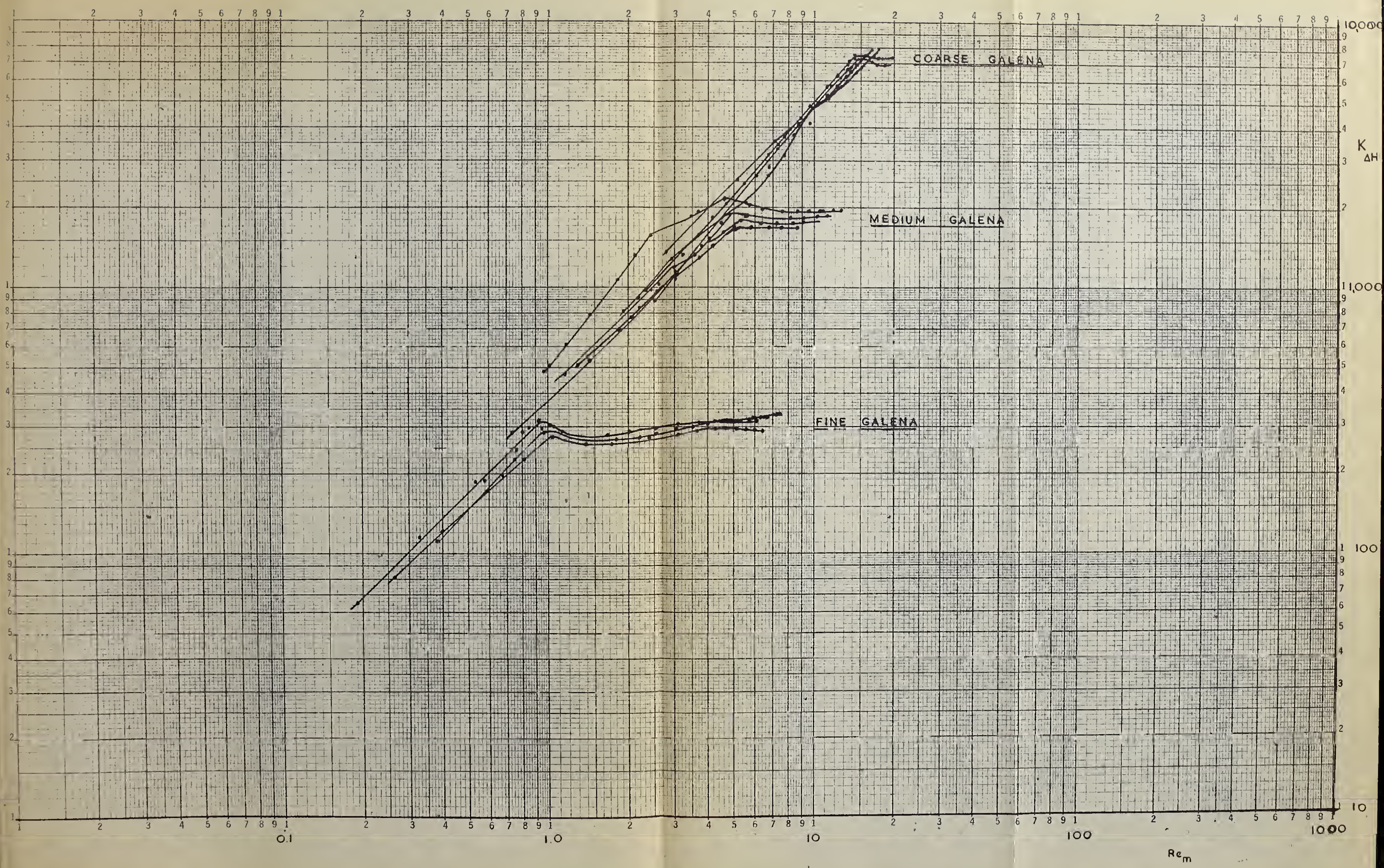
GRAPH SHOWING THE RELATIONSHIP BETWEEN $K_{\Delta H}$ AND THE REYNOLDS NUMBER FOR SAND.



COARSE SAND
MEDIUM SAND
FINE SAND
$K_{\Delta H}$
10,000
1000
100
10
0.1
1.0
10
100
1000
R_{e_m}

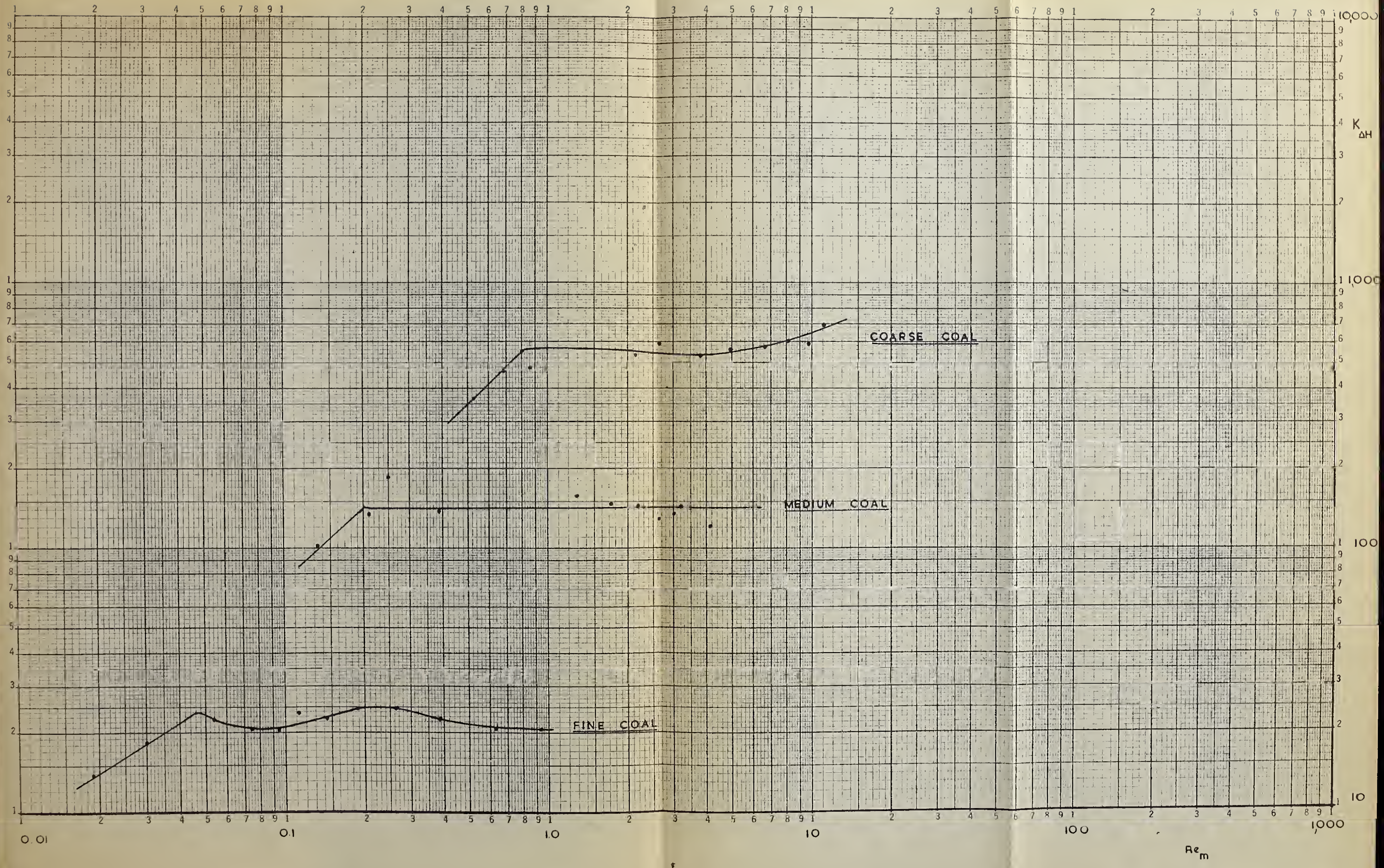
(Figure 40)

GRAPH SHOWING THE RELATIONSHIP BETWEEN $K_{\Delta H}$ AND THE REYNOLDS NUMBER FOR GALENA.


COARSE GALENA
MEDIUM GALENA
FINE GALENA
$K_{\Delta H}$
10,000
1,000
100
10
Re_m
0.1
1.0
10
100
1000

(Figure 41)

GRAPH SHOWING THE RELATIONSHIP BETWEEN $K_{\Delta H}$ AND THE REYNOLDS NUMBER FOR COAL.


COARSE COAL
MEDIUM COAL
FINE COAL
$K_{\Delta H}$
10,000
1,000
100
10
Re_m
0.01
0.1
1.0
10
100
1,000

graph is considerably wider, than the graphs presented here, as far as the higher Reynolds Numbers are concerned, but does not extend to as low Reynolds Numbers.

The data on the preceding four graphs is systematized in Figure 42. Whereas Wilhelm and Kwauk used Wadell's data(10) for the construction of the line representing free settling conditions, in Figure 42 this line has been established from the data of Schiller and Nauman.

The curves representing consolidated bed conditions for the three materials, are parallel but not coincident. However, the displacement does not exceed that shown by the published data.

None the less, whilst they are parallel to the mean line for bed conditions given by Wilhelm and Kwauk, they are all situated somewhat lower.

Since the experimental conditions and particle sizes used in the two series of experiments were different, a strict comparison of the portions of the curves representing teetering conditions is not possible.

OBSERVATIONS

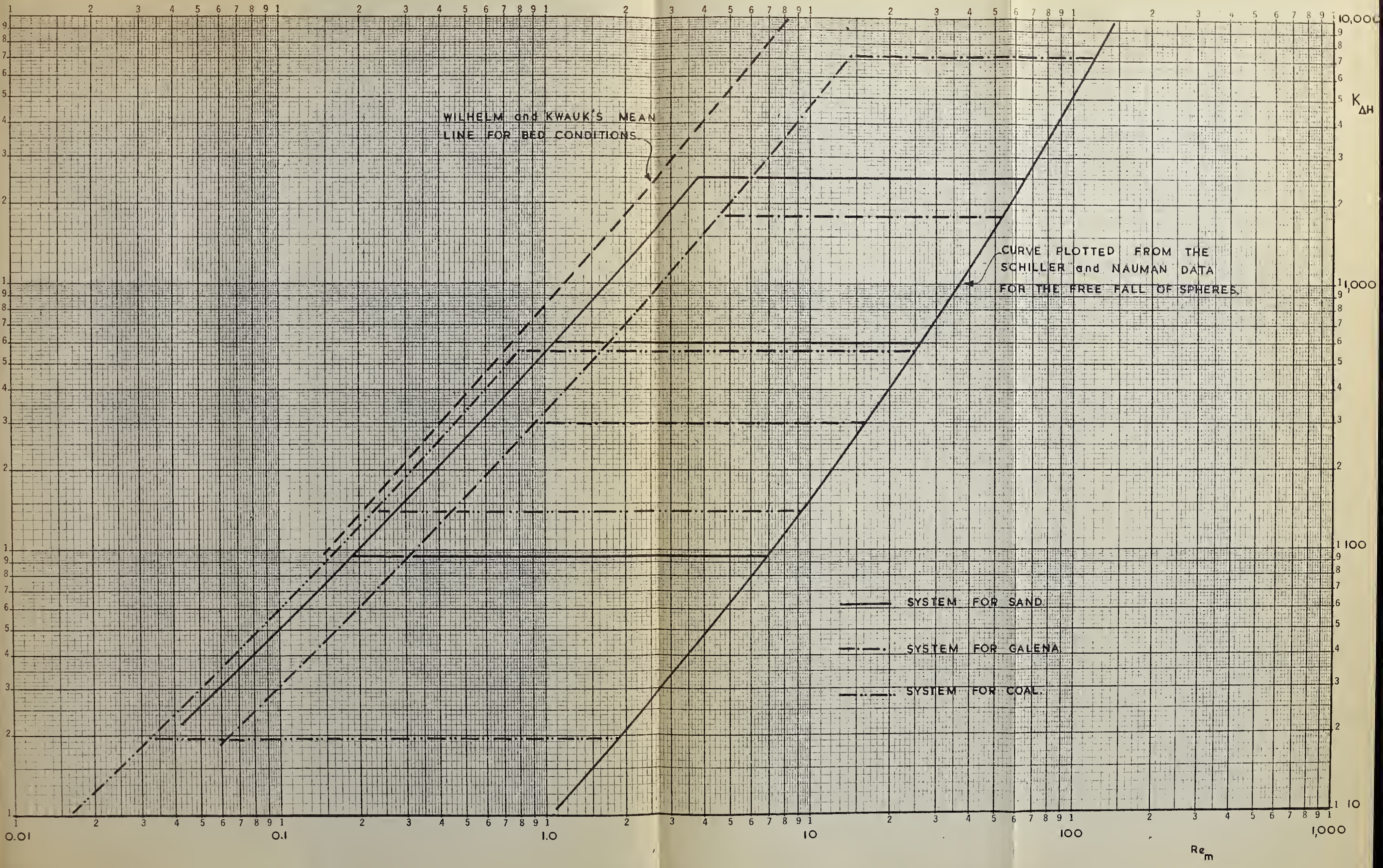
(a) Voidage

Wilhelm and Kwauk further present a generalized correlation between $K_{\Delta p}$, Re_m and ϵ for particulate fluidization, but the relationships shown in this correlation are questioned by L. Friend,(9) who demonstrated that subject to certain reservations there was considerable disagreement with data established by the M. W. Kellogg Company.

Calculations of percentage voidage have been made but are not superimposed on Figure 42 in the interests of clarity. It will suffice

(Figure 42)

SYSTEMATISED REPRESENTATION OF
FIGURES 39, 40 & 41.


WILHELM and KWAUK'S MEAN LINE FOR BED CONDITIONS.
CURVE PLOTTED FROM THE SCHILLER and NAUMAN DATA FOR THE FREE FALL OF SPHERES.
SYSTEM FOR SAND.
SYSTEM FOR GALENA.
SYSTEM FOR COAL.
0.01
0.1
1.0
10
100
1,000
Re_m
10
100
1,000
10,000
$K_{\Delta H}$

however to state that these calculations show that as suggested by Friend, the percentage voidage curves given by Wilhelm and Kwauk may only be acceptable for the experimental conditions with which they were dealing.

It may also be pointed out that plots of Re_m v. ϵ for the experiments described in this thesis, as for example Figure 43 for sand, differs markedly from a similar plot given by Wilhelm and Kwauk, (Figure 10, loc. cit.).

In the case of the latter, the change from the consolidated bed to the fluidized state is represented by a sharp and definite break in the curve, whereas in Figure 43 there is a gradual transition. The explanation for this difference presumably is that the beds used by these investigators were in a densely packed condition and hence firmly interlocked. Unless the fluid velocity through such a bed is increased very slowly, the change from a tightly locked to a fluidized condition, is likely to occur suddenly, resulting in the sharp inflexion of the curve. The consolidated beds used in the foregoing experimental work were not employed in their densest condition and accordingly the curves obtained show a smooth gradation.

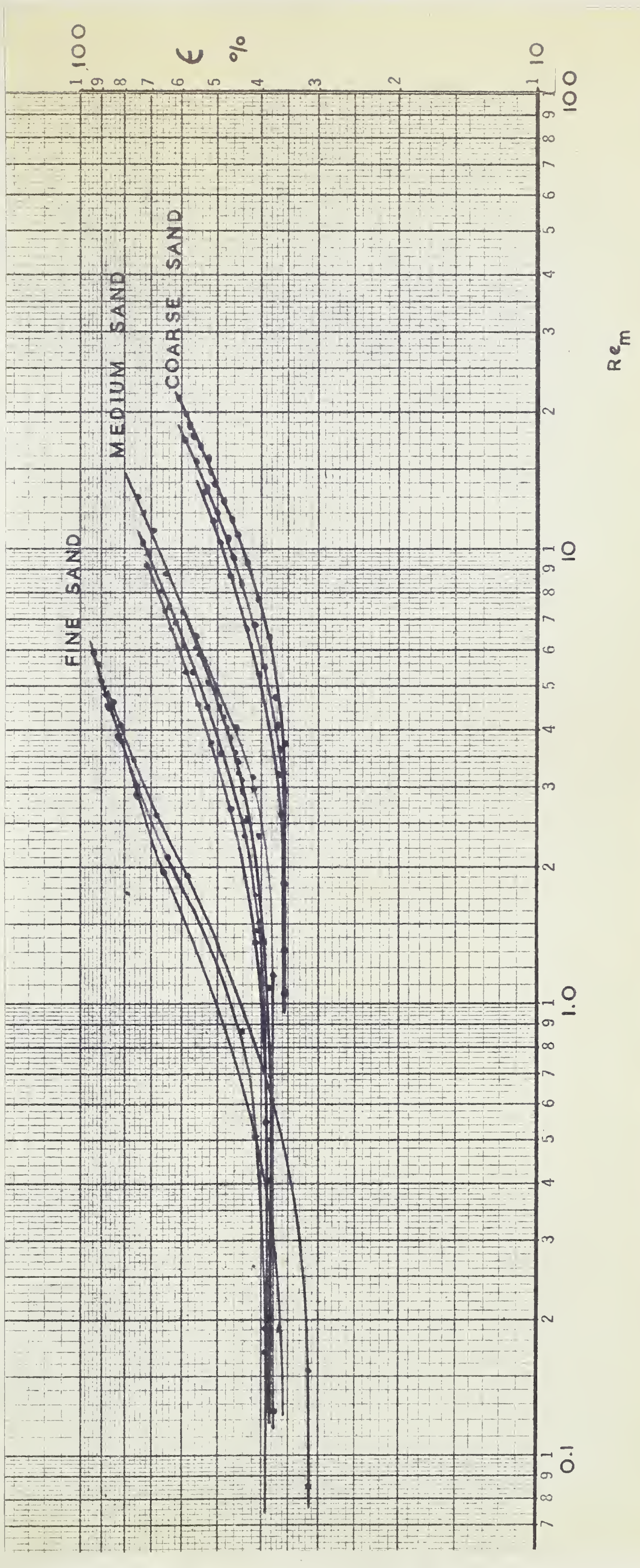
It is important to notice that Wilhelm and Kwauk state that the proposal by Hancock (loc. cit.) that a single function of the voidage can be used to correlate data of the type under consideration was found to be quite unsatisfactory.

The reasons for this are quite clear in view of the preceding discussion under Analytical Treatment (1).

Apart from stating that Hancock's proposal was found to be unsatisfactory, Wilhelm and Kwauk make no attempt to elucidate the matter

(Figure 43)

GRAPH SHOWING THE RELATIONSHIP BETWEEN
THE REYNOLDS NUMBER AND THE VOIDAGE
FOR THREE SIZES OF SAND.


ε %
Re_m
FINE SAND
MEDIUM SAND
COARSE SAND
1 100
10
2
3
4
5
6
7
8
9
1 10
0.1
1.0
10
100

of voidage.

(b) The Characteristic Curve

A characteristic or typical fluidization curve relating pressure drop to fluid flow is shown in Figure 44.

The description given by the above investigators of the significance of this curve can be extended, particularly if consideration is given to Figures 22 and 23 for galena.

Whereas, using many types of material the region between B and D is unavoidably traversed rapidly owing to an inherent instability of the bed (and precise measurements in this region cannot be obtained), in the case of galena, the significant measurements may be made and the form of the curve in this region precisely established as is well shown in Figure 22.

To quote Wilhelm and Kwauk, the "deviation from linearity at B (which) is characteristic of minor movement and readjustment of particles in the bed to offer the largest possible free cross-sectional area to flow" is shown in Figure 23 in a particularly striking manner.

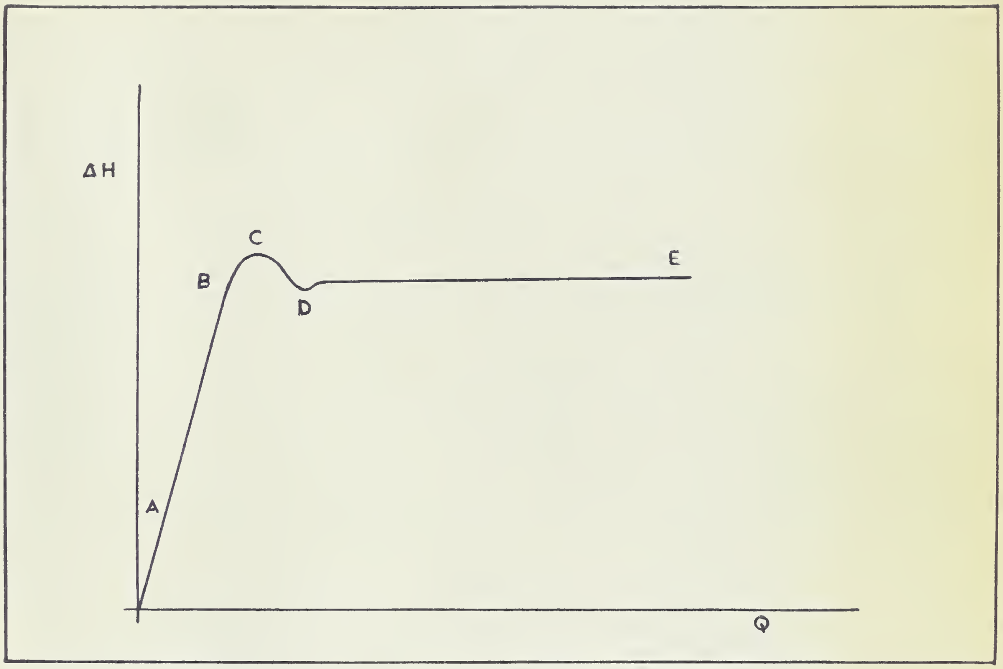
The several inflections on what otherwise has been considered the straight portion AB, especially notable as the depth of bed increases, presumably represent a series of quite specific re-orientations of the particles in the bed.

Owing to the angular nature of the particles and to their high reflective power, these transitional movements were readily observable visually.

(c) Effect of Particle Size

(Figure 44)

TYPICAL FLUIDISATION CURVE RELATING
PRESSURE DROP TO FLUID FLOW.


ΔH
C
E
B
D
A
Q

The effect of particle size upon the pressure drop can be seen by considering the relationship of $\left(\frac{\Delta H}{L_o}\right)$ fl. to the flow of fluid. That is, $\left(\frac{\Delta H}{L_o}\right)$ fl. to Q .

The values for ΔH for the fluidized state can be taken from Figures 17 - 19 and 22 - 27, and for L_o from the tabulated data.

The minimum and maximum values for the ratio, $\left(\frac{\Delta H}{L_o}\right)$ fl. are given in Table LXXX.

TABLE LXXX

Material	Size	Minimum Value	Maximum Value	Average Value
Sand	Fine	1.35	1.54	1.45
	Medium	1.39	1.52	1.46
	Coarse	1.38	1.48	1.43
Galena	Fine	4.17	4.56	4.37
	Medium	4.4	4.69	4.55
	Coarse	4.5	4.6	4.55
Coal	Fine	0.27		
	Medium	0.33		
	Coarse	0.42		

The values for sand are substantially those for like material obtained by Wilhelm and Kwauk.

It will be seen that in the fluidized state, the pressure drop related to unit depth of settled bed, is independent of the size of particle, with any particular material.

This is in accordance with the formula used by Andrews relating to the formation of quicksand beds, quoted in texts on soils mechanics. (p.52).

Andrews formula is:-

$$P = \frac{L \times (s - p)}{1 + e}$$

Using the notation subsequently adopted this becomes

$$\Delta P = \frac{L\,(\rho s - \rho f)}{\frac{L}{L_o}} \text{ , (since } 1 + e = \frac{L}{L_o}\text{)}$$

Hence $\frac{\Delta P}{L_o} = (\rho s - \rho f)$

or $\frac{\Delta H}{L_o} = \frac{(\rho s - \rho f)}{\rho f}$

(d) Effect of Density of Material

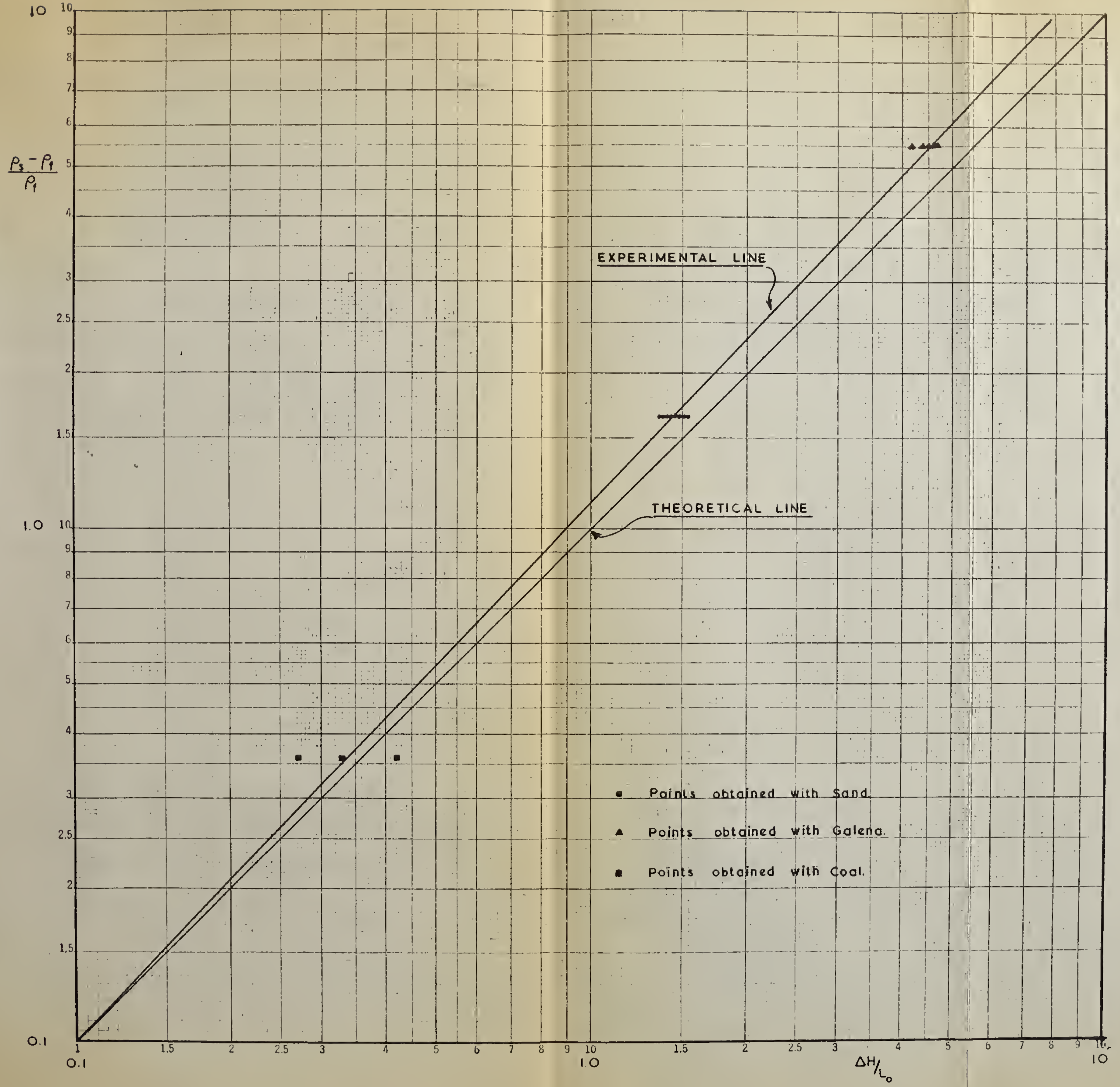
Figure 45 shows the relationship between the effective density $\frac{\rho s - \rho f}{\rho f}$ and the pressure drop index, $\left(\frac{\Delta H}{L_o}\right)$ fl. for the different materials used.

As demonstrated on p.191 points on this graph should fall on a straight line of slope 1.0. In actual fact the line has a slope of 1.05.

No explanation can be advanced for this other than possibly experimental differences introduced by the apparatus and materials employed. It may be noted that in a similar graph drawn by Wilhelm and Kwauk (Figure 12 loc. cit.), the points do not lie precisely on the theoretical line.

(Figure 45)

GRAPH SHOWING THE RELATIONSHIP BETWEEN THE PRESSURE DROP PER UNIT OF REDUCED DEPTH OF BED, $\frac{\Delta H}{L_o}$, AND THE DENSITY RATIO, $\frac{\rho s - \rho f}{\rho f}$


$\frac{\rho_s - \rho_f}{\rho_f}$
10
1.0
0.1
EXPERIMENTAL LINE
THEORETICAL LINE
● Points obtained with Sand.
▲ Points obtained with Galena.
■ Points obtained with Coal.
0.1
1.0
10
$\Delta H / L_o$

SUMMARY

The work described in this thesis may be summarized as follows:-

PART I

A survey of the preparation of coal for the market in Alberta, based on a detailed questionnaire completed by the managements of certain coal mines in the province, has shown that:-

(a) Coal cleaning, apart from handpicking, is restricted to mines in the bituminous regions.

(b) The proposal has been put forward that the practice in the sub-bituminous mines might profitably be modified, by the introduction of adequate sizing machinery to allow of a widening of the range of sizes of coal marketed for stoker purposes. In brief, the proposal is that the lower size limit should be reduced to at least $\frac{1}{4}$ inch.

Inherent in this proposal is the view that, thereby, considerable quantities of coal now sold at low prices or wasted by dumping, would ~~thereby~~ be used more economically.

(c) Both in the sub-bituminous and bituminous mines, there is scope for the commencement of a study on methods of coal breakage.

(d) Since in the bituminous mines in particular, coal cleaning practice varies considerably, no proposals are made with a view to securing uniformity in the nomenclature and sizing of marketed products.

(e) The survey reveals that there are instances where the prevailing operation of coal cleaning plants might be improved.

(f) Interesting detailed information on coal sizes in products marketed by both the bituminous and sub-bituminous operators has been tabulated for ready reference.

PART II

(a) A survey of the literature dealing with scientific investigations on fundamental problems relating to the behaviour of solid particles in teetering beds arising from particular work on the cleaning of fine coal, has indicated that published work up-to-date⊖ has not provided any adequate mathematical relationship between the behaviour of a particle settling freely in an infinite body of fluid (free settling) and like particles in a teetering bed (hindered settling).

(b) Experiments have been carried out on teetering beds of sand, galena and coal to establish experimental data as a basis for correlation with published work on free settling and fluidization.

(c) The correlation worked out has emphasized the importance of voidage to which, apparently, too little attention has been paid in the past.⊖ The voidage factors proposed and used by former workers have been shown as not truly representing the facts.

(d) A correct representation is that the function of the voidage to be employed in a modified expression relating resistance to flow, to the other variables in the system, is one which has the form of an infinite series.

(e) Since the use of an infinite series makes the problem unduly complex for computational purposes, approximate expressions have been proposed for the voidage function.

(f) It has been shown that use of these approximate expressions makes possible the prediction of the behaviour of teetering beds by employing methods hitherto applied to conditions of free settling.

Detailed consideration of the published work of M. Leva and M. Grummer (p. 228) might give rise to some modification of these conclusions.

⊖ See p. 228.

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

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loc. cit.

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The Mining Magazine, 1942, 67, 179.

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(10) H. Wadell
Physics, 1934, 5, 281.

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The examiners have drawn attention to the following series of articles which also deal with the fundamentals of fluid flow through consolidated and fluidised beds.

M. Leva.
Chemical Engineering Progress 1947, 43, 549

M. Leva, M. Grummer.
Chemical Engineering Progress 1947, 43, 633.

M. Leva, M. Grummer.
Chemical Engineering Progress 1947, 43, 713.

These workers have presented extensive data on the effect of bed voidage, particle shape and particle roughness as significant factors in determining the flow and pressure drop relationships."

NOMENCLATURE

L = depth of the bed in the consolidated, expanded or teetering condition. (cms.)

ΔH = Differential head of water as measured between the level of water in the constant level tank, A, and the level of water in the constant head device, B, (cms.)

V = volume of water collected (ml.)

t = time for collection of water (sec.)

Q = rate of flow of water. (mls/sec.)

ρ_f = density of fluid medium (g./ml.)

ρ_s = density of material composing the bed (g./ml.)

Δ = effective density of the system, e.g. the density of suspension of sand in water. (g./ml)

μ = viscosity of fluid (lb./ft. sec.)

D_p = mean diameter of particle (ins.)

u_m = linear velocity of fluid flow in empty tube (ft/sec)

W = mass flow of fluid (lb/sec)

ϵ = fractional free space in bed

u_t = velocity of free falling particle in still fluid (ft/sec.)

u_i = fluid velocity in interstices of bed (ft/sec.)

Re_m= modified Reynolds Number based on condition in empty tube, (dimensionless)

F = viscous drag to which particles are subjected (ft. lbs/sec^2)

ψ = correlating group, $\frac{4}{3}\frac{D_p \cdot g}{u_m^2}\left(\frac{\Delta H}{L_o}\right)$, (dimensionless)

ψ' = correlating group, $\frac{4}{3}\frac{D_p \cdot g}{u_m^2}\left(\frac{\Delta H}{L_o}\right)f(\epsilon)$ (dimensionless)

Note. The English Absolute system of units is used throughout. In this system, the dimension conversion quantity, g, has a numerical value of 32.2 but is dimensionless."

B29756